Investigating the influence of tides, inflows, and exports on sub-daily flows at junctions in the Sacramento-San Joaquin Delta

(excerpts of introduction, methods, figures and tables prepared to date)

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"*One can judge from experiment, or one can blindly accept authority. To the scientific mind, experimental proof is all important…theory is merely a convenience in description, to be junked when it no longer fits. To [some], authority is everything and facts are junked when they do not fit theory laid down by authority*."

Dr. Pinero, Life-Line (1939) by Robert Heinlein

Introduction

The relative influence of tides, inflows, and exports on flow patterns in California's Sacramento-San Joaquin Delta (Delta) continues to be a source of confusion and uncertainty for resource managers. The potential for impacts to sensitive fish species from export pumping, in particular, remains highly contentious and has been the focus of two recently remanded Endangered Species Act Section 7 biological opinions (USFWS 2008; NMFS 2009). The Particle Tracking Model (PTM), which has become a standard analytical tool for assessing Delta flow patterns, has been used to evaluate entrainment risks for larval delta smelt (Culberson et al. 2004; USFWS 2008; Kimmerer and Nobriga 2008; BDCP 2011) and also for juvenile salmonids (NMFS 2009). However, these applications of the PTM have significant limitations which may be relevant to delta smelt and especially to juvenile salmon. Specifically, the PTM has typically been used to depict net water movement within Delta channels—and the Delta as a whole—over one to three months. The PTM has not been typically been used to describe daily or sub-daily variations in flow due to the interaction of tides with river inflows and exports. Yet, for migrating juvenile salmonids, sub-daily and/or daily flows have been shown to be determinative of route selection at the junction of Georgiana Slough on the Sacramento River, and the Head of Old River on the San Joaquin River.

In light of these limitations of PTM for migrating juvenile salmonids, we have taken a different approach to analyzing water movement in the Delta at junctions and in the Delta as a whole. Using data from the Delta Simulation Model-2 hydrodynamics model (DSM2 Hydro), we describe variation in key flow variables caused by changes in South Delta exports and river inflows. Borrowing from the approach of Kimmerer and Nobirga (2008) by using simulated data with fixed tidal cycles and other inputs, we are able to reveal patterns of exports and river inflows at a spatial and temporal scale necessary to evaluate the influence migration and survival of migrating fish.

At the junction scale, the need to couple detailed hydrodynamic data with acoustic tagging data has been recognized (Vogel 2004). To this end, we combine DSM2 Hydro flow data at 15-minute intervals with insights gained from recent acoustic tagging studies (e.g., Holbrook et al. 2009; Perry et al. 2010) to obtain a detailed description of how tides, river inflows, and exports interact to influence juvenile salmonid route selection at eight junctions along the mainstem San Joaquin River.

This document provides a summary of figures and tables completed to date which can help inform discussions about studies needed and available to inform OCAP litigation and for drafting of the remanded Biological Opinion. We are actively preparing a manuscript for peer review publication which describes our findings on the the effect of exports and inflows on route selection for migrating juvenile salmonids. Subsequent manuscripts describing spatial and longitudinal patterns, and considering additional inflow/export scenarios may also be desirable.

Methods

For our investigation, we identified all of the junctions at which the action of tides, inflows, and exports may divert migrating fish from the San Joaquin River into the interior Delta (Figure 2). We also included the junction of Georgiana Slough and the Sacramento River; Georgiana Slough is the primary waterway by which migrating salmonids enter the interior Delta from the Sacramento River, particularly when the Delta Cross Channel (DCC) gates are closed. Flow patterns in these junctions were analyzed using simulated flow data from the Delta Simulation Model-2 Hydrodynamics (DSM2 Hydro) model.

To facilitate analysis and discussion of DSM2 Hydro data, we constructed a schematic plan-view for each channel junction and labeled channels sequentially in a clockwise fashion (for example, *see* Figure 6). A summary of channel labels and corresponding DSM2 Hydro designations can be found in Table 2. DSM2 channel 31, which is shared by the Turner Cut and Columbia Cut junctions, was given a designation for each of these junctions. The plan-view depictions of channel junctions were an essential step in interpreting DSM2 Hydro data; they were used to visually identify upstream and downstream channels, and to determine physical flow directions for which water from upstream and/or downstream could be diverted to the interior Delta at each junction.

In order to better understand the relative influence of tides, inflows, and exports on flows to the interior Delta, we analyzed the proportion of flow over 24 hours at all of the junctions. For calculation purposes, water which flowed into a junction was termed "input" (I) when the direction of flow was toward (rather than away from) the center of the junction; water which flowed into the interior Delta was termed "output" (O). At each 15-minute time interval provided by DSM2 Hydro, the proportion of flow entering the interior Delta (ρ_{jt}) was calculated as:

$$\rho = \frac{O_{jt}}{I_{jt}},$$

where O_{jt} is the flow (cfs) entering the interior Delta at junction *j* at 15-minute time interval *t*, and where I_{jt} is the total inflow (cfs) entering from junction *j* channels at 15-minute time interval *t*. Calculations were made under the following assumptions:

a) ρ could not exceed 1.
b) When O_{jt} was toward the center of the junction (i.e., when flow was leaving the interior Delta instead of entering it), ρ was set to zero.

Regarding the source(s) of water flowing into the interior Delta (I_{jt}), we assumed:

c) A channel only contributed to I_{jt} at time interval *t* if the physical direction of flow in that channel was toward the center of the junction at time interval *t*.
d) If only one channel contributed to I_{jt} at time interval *t*, then all water flowing into the interior Delta (O_{jt}) originated from that channel at time interval *t*.
e) If multiple channels contributed to I_{jt} at time interval *t*, then water flowing into the interior Delta (O_{jt}) was a mixture of water from the channels; the relative contribution of each input channel was proportional to the relative magnitude of flow in that channel at time interval *t*.

Using these assumptions, and following methods described by Perry (2010) we calculated the daily proportion of flow entering the interior Delta (ρ_{jd}) at each junction as:

$$\rho_{jd} = \frac{\sum_{t=1}^{96} {}^{O_{jt}}/_{I_{jt}}}{96}.$$

In instances where calculation results for proportion of flow were equal to or greater than 100%, the values were capped at 100%. This was done under the assumption that “extra” water output to the interior Delta must have been input to the junction previously. However, it is also possible that values greater than 100% indicate a breakdown of the DSM2 Hydro simulation at these points. An examination of this possibility was beyond the scope of our investigation.

Empirical Basis for Using Flow Proportion as a Predictor of Juvenile Salmonid Route Selection at Junctions

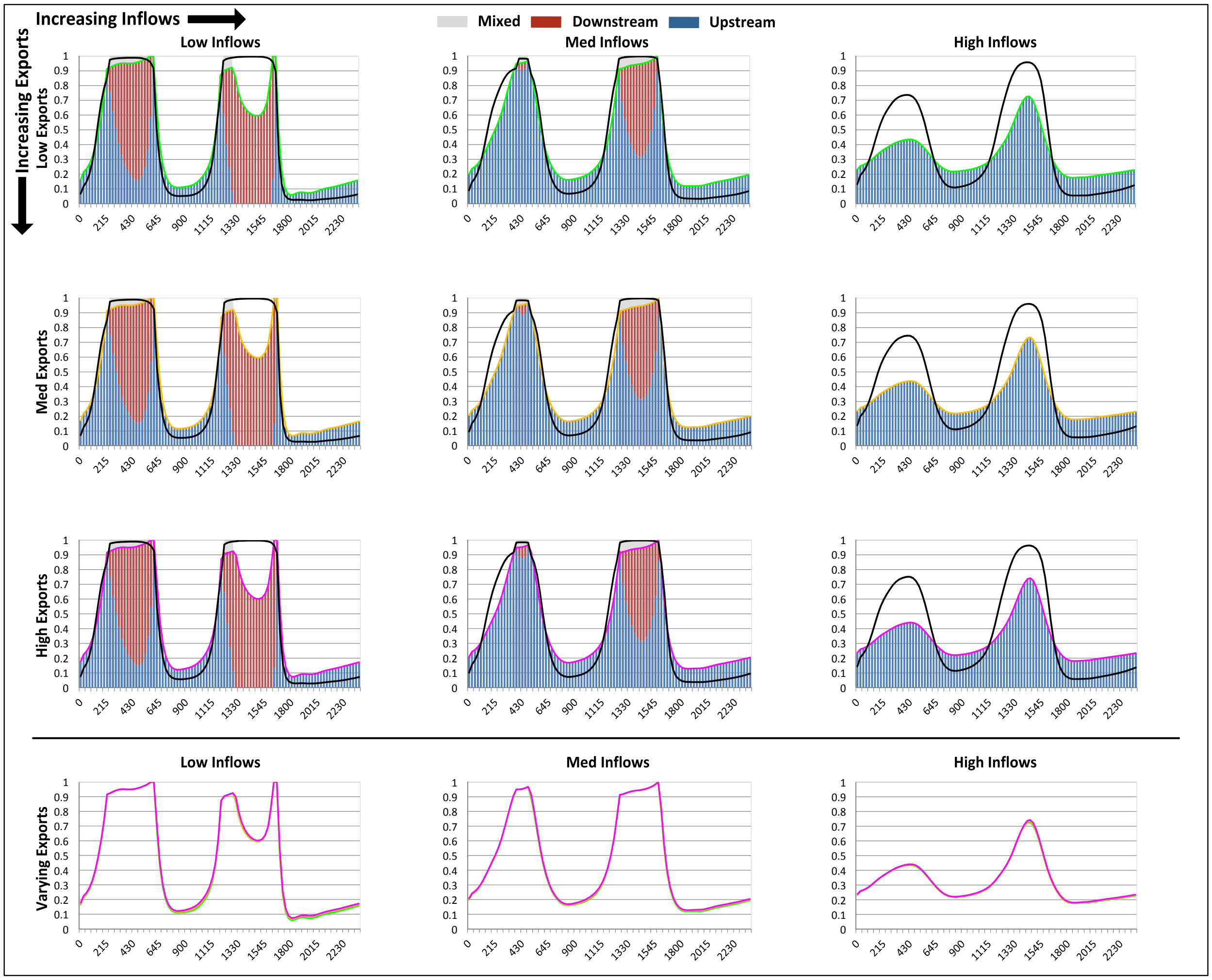


Figure 1. GEO: Proportion of Flow to Georgiana Slough with predicted probability of juvenile salmonid entrainment using Perry 2010 equation 6.4. Time of day in 24-hr format is on the x-axis; proportion of flow is on the y-axis. Graphs in the top section display the proportion of water input to the junction which is output to Georgiana Slough (curve), by water source (bars under the curve). Curve color indicates export level. Bar color indicates water source; bar height indicates relative proportion. Gray shading indicates water from more than one source. Black curves superimposed on the proportion of flow graphs are the probability of entrainment into Georgiana Slough, as calculated from equation 6.4 of Perry 2010. Graphs in the top section are arranged by increasing inflows and exports. Graphs in the bottom section compare proportions under varying exports, with the bars removed for clarity.

Delta Hydrodynamics:

Channel Junction Analysis

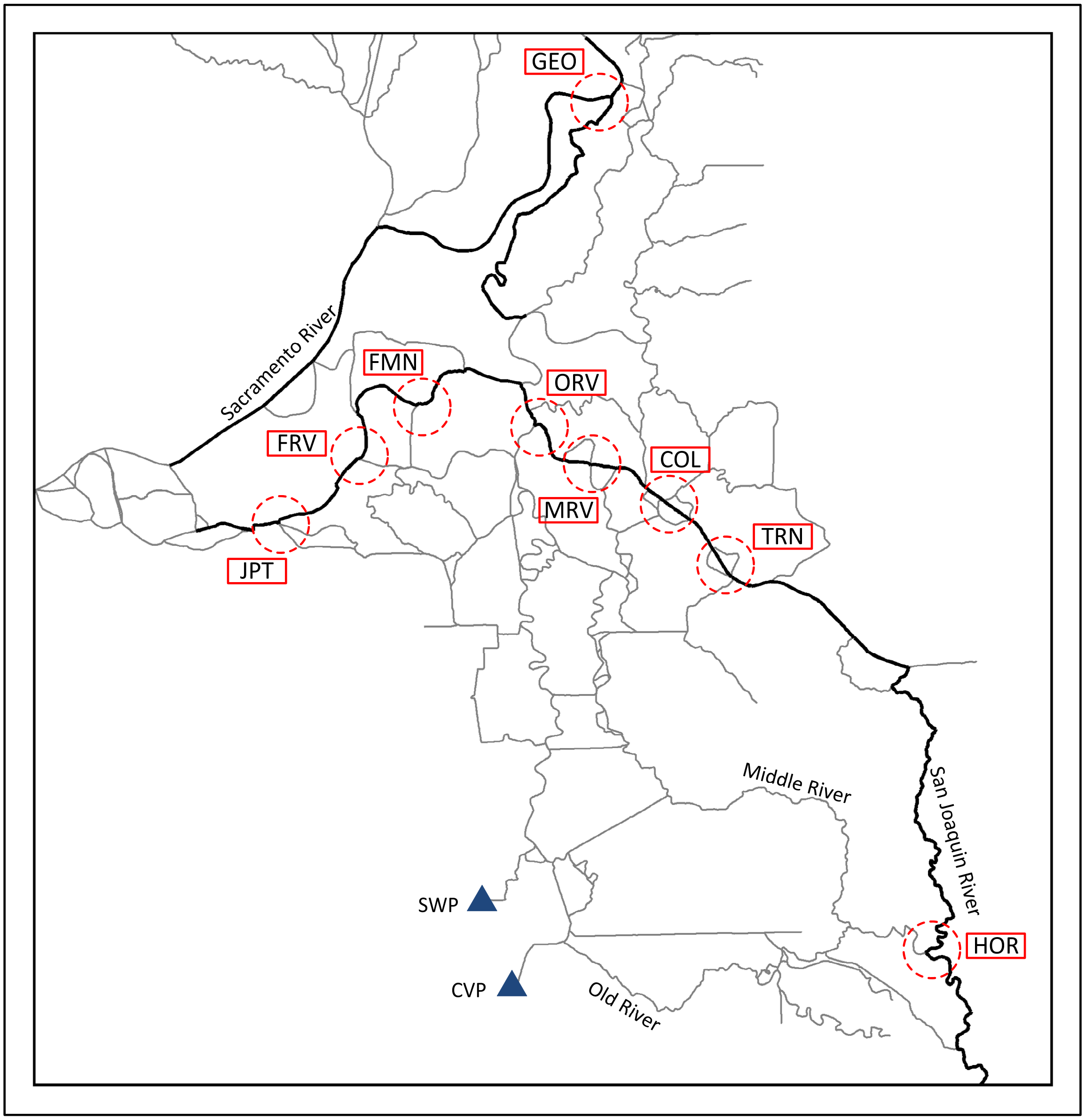


Figure 2. Location of Junctions Leading to the Interior Sacramento-San Joaquin Delta. Georgiana Slough, mainstem Sacramento River, and mainstem San Joaquin River are indicated in black. Junction locations are circled in red and designated as follows: GEO=Georgiana Slough, HOR=Head of Old River, TRN=Turner Cut, COL=Columbia Cut: MRV=Middle River, ORV=Mouth of Old River, FMN=Fisherman's Cut, FRV=False River, JPT=Jersey Point. Export facility locations are indicated by blue triangles; SWP is the State Water Project, CVP is the Central Valley Project. Note that the channel upstream of HOR which is visible in the figure and appears to connect to the San Joaquin River does not actually do so.

Table 1. Conditions of river inflow, South Delta exports, OMR and Inflow to Export (I:E) ratio evaluated in the following analyses.

Inflow San Joaquin	DCC Gate Position	Total Exports	I:E Ratio	OMR
Low (3,000 cfs)	Closed	Low (2,989 cfs)	1.0	-2,500
Low (3,000 cfs)	Closed	Med (4,053 cfs)	0.7	-3,500
Low (3,000 cfs)	Closed	High (5,649 cfs)	0.5	-5,000
Med (6,000 cfs)	Closed	Low (3,241 cfs)	1.9	-2,500
Med (6,000 cfs)	Closed	Med (4,305 cfs)	1.4	-3,500
Med (6,000 cfs)	Closed	High (5,901 cfs)	1.0	-5,000

Table 2. DSM2 Hydro channels, junction-specific abbreviations, and channel designations. Arrows indicate the direction of positive flows between nodes as defined in the DSM2 Hydro model. Channels leading to the interior Delta are indicated in bold. Channels upstream of a junction are indicated in blue; downstream channels are indicated in red. For Columbia Cut, Disappointment Slough is indicated in aqua; a secondary downstream channel (COL7) is indicated in orange.

Junction	Jct. Abbrev.	DSM2 Nodes	DSM2 Channel	Designation
Head of Old River	HOR	7→8	7	HOR2
		8→9	8	HOR1
		8→48	**54**	**HOR3**
Turner Cut	TRN	25→26	25	**TRN3**
		26→27	26	TRN1
		26←28	27	TRN7
		27→29	28	TRN2
		28←29	29	TRN6
		26→29	30	TRN4
		29→30	31	**TRN8**
		26←140	**172**	**TRN5**
Columbia Cut	COL	29→30	31	**COL3**
		30→31	32	COL5
		32→31	33	COL9
		30→32	34	COL4
		31→33	35	**COL7**
		32→33	36	**COL8**
		31←133	**160**	**COL6**
		30←244	315	COL1
		32←244	316	COL2
Middle River	MRV	33→34	37	**MRV3**
		34→35	38	MRV4
		35→36	39	MRV1
		36→37	40	MRV2
		35→37	41	MRV8
		37→38	42	**MRV9**
		133→134	**161**	**MRV5**
		34←134	162	MRV7
		35←134	163	MRV6
Mouth of Old River	ORV	37→38	42	**ORV1**
		38→39	43	**ORV3**
		38←103	**124**	**ORV2**
Fisherman's Cut	FMN	41→42	46	**FMN1**
		42→43	47	**FMN3**
		42→226	**280**	**FMN2**
False River	FRV	43→44	48	**FRV3**
		44→469	83	**FRV2**
		44→226	**279**	**FRV1**
Jersey Point	JPT	45←469	49	**JPT1**
		45→461	50	**JPT3**
		45←76	**260**	**JPT2**

Head of Old River (HOR) Junction:

Junction Plan View

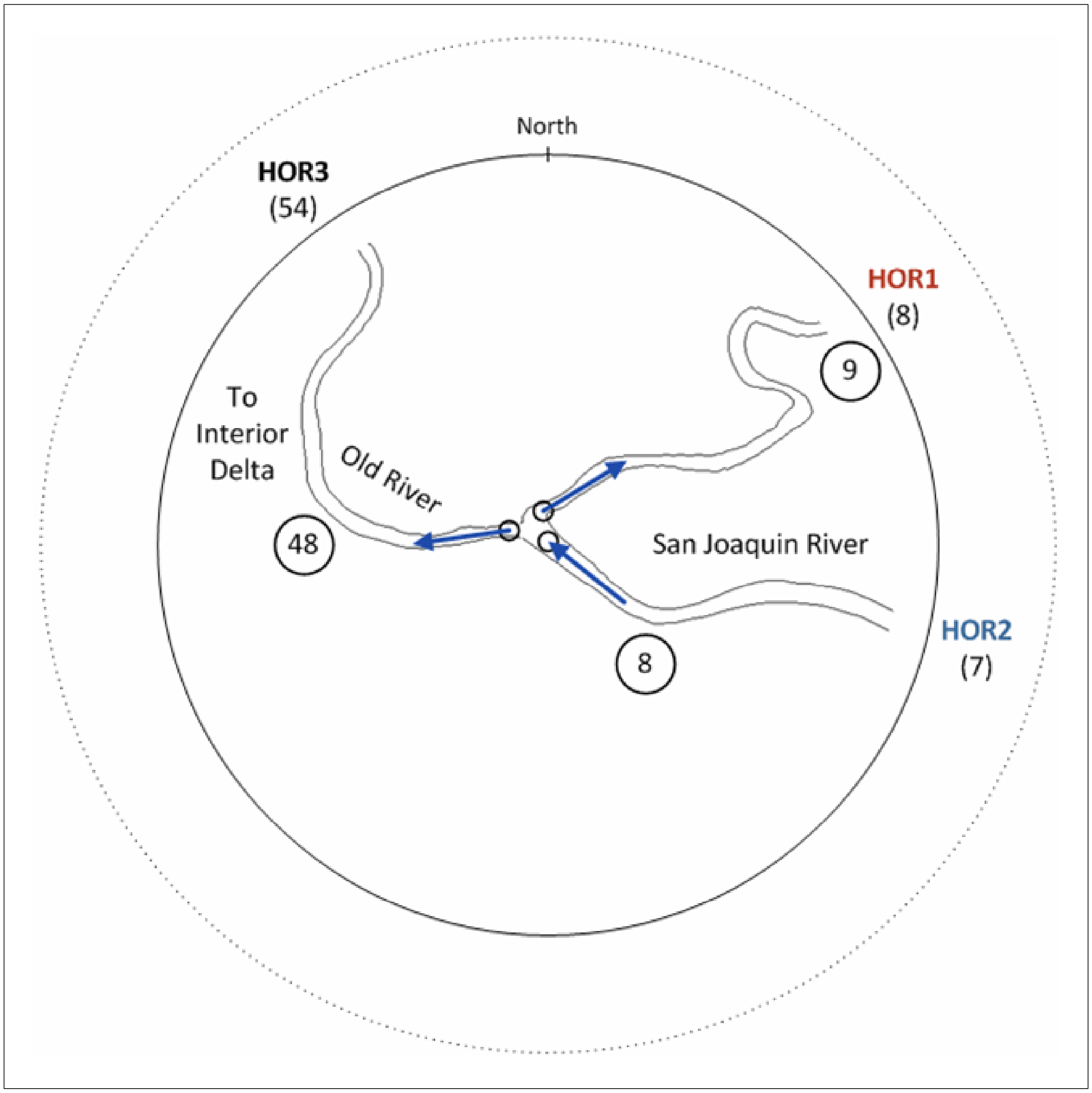


Figure 3. HOR: Plan-view of Head of Old River Junction. Physical channel outlines are shown in gray. DSM2 Hydro channel numbers are given in parentheses, nodes are circled, and positive flow direction in each channel is indicated by blue arrows. Upstream, downstream, and to interior Delta channels are indicated as in Table 2.

Head of Old River (HOR) Junction:

Flows

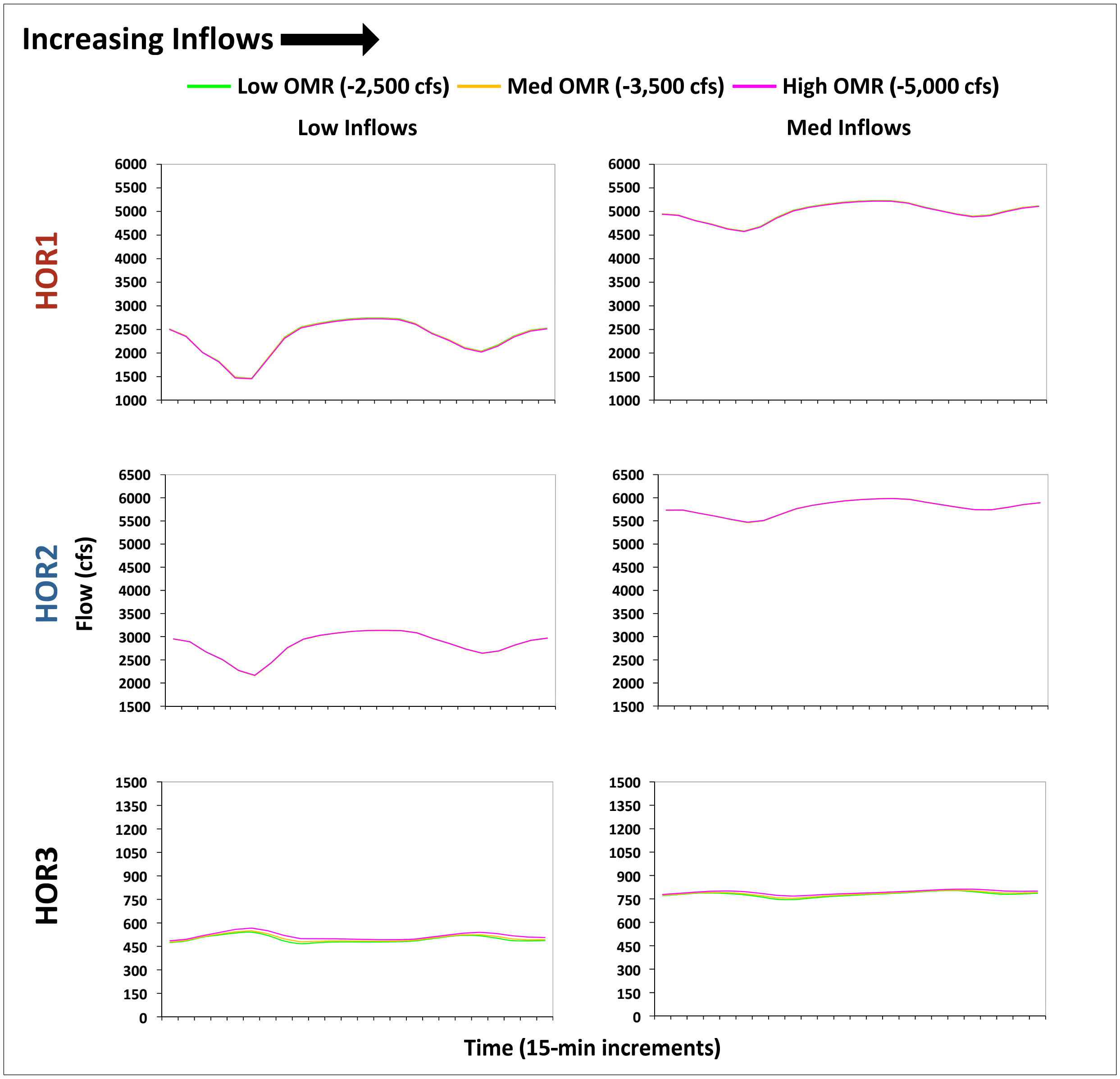


Figure 4. HOR: Flow in Head of Old River Junction Channels over 24 Hours. Time is on the x-axis; magnitude of flow is on the y-axis. Curve color indicates export level. Chanel designations are as indicated in Table 2.

Head of Old River (HOR) Junction:

Proportion of Flow to Interior Delta

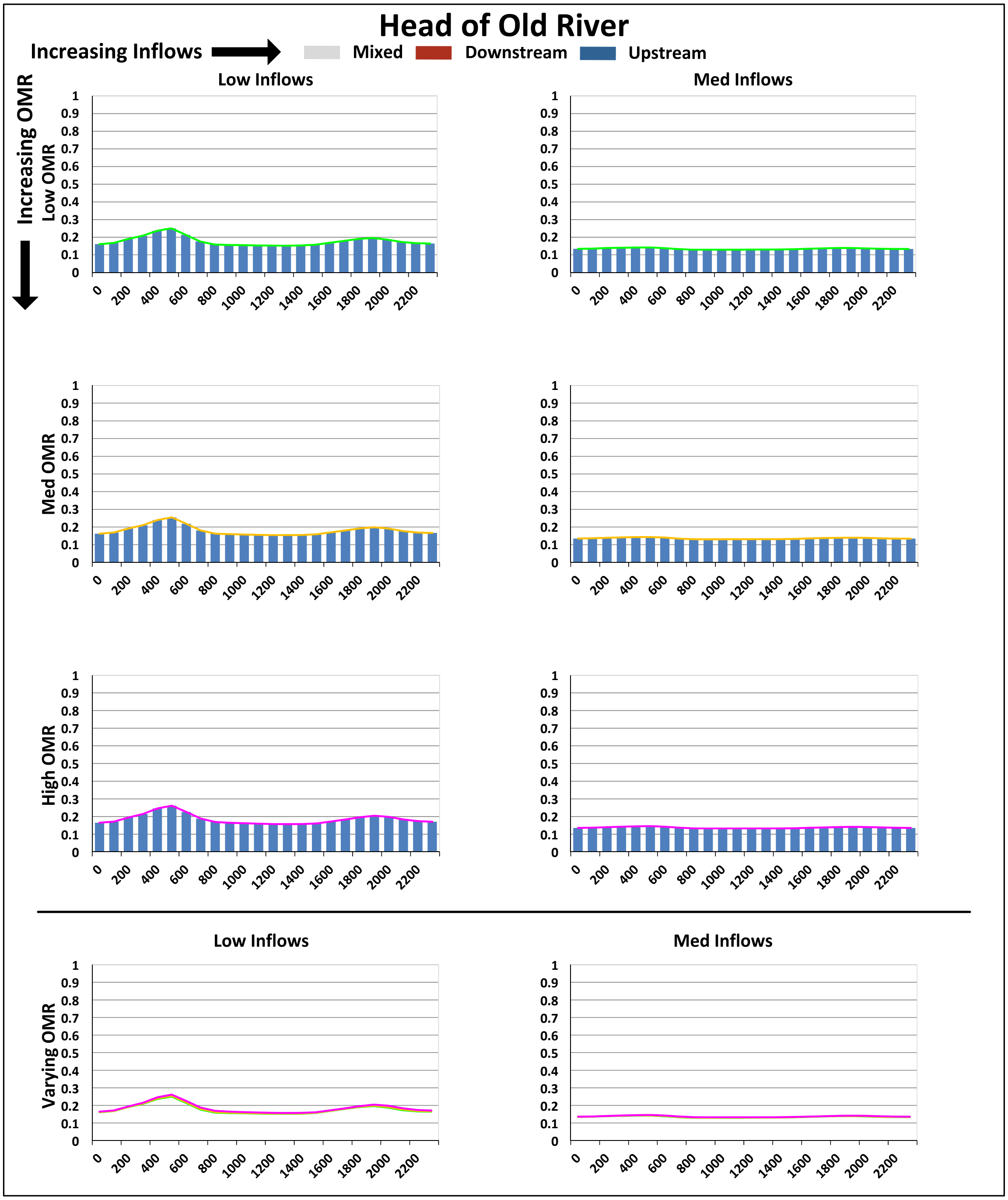


Figure 5. HOR: Proportion of Flow to Interior Delta at Head of Old River. Time of day in 24-hr format is on the x-axis; proportion of flow is on the y-axis. Graphs in the top section display the proportion of water input to the junction which is output to the interior Delta (curve), by water source (bars under the curve). Curve color indicates export level. Bar color indicates water source; bar length indicates relative proportion. Gray shading indicates water from more than one source. Graphs in the top section are arranged by increasing inflows and exports. Graphs in the bottom section compare proportions under varying exports, with the bars removed for clarity.

Turner Cut (TRN) Junction:

Junction Plan View

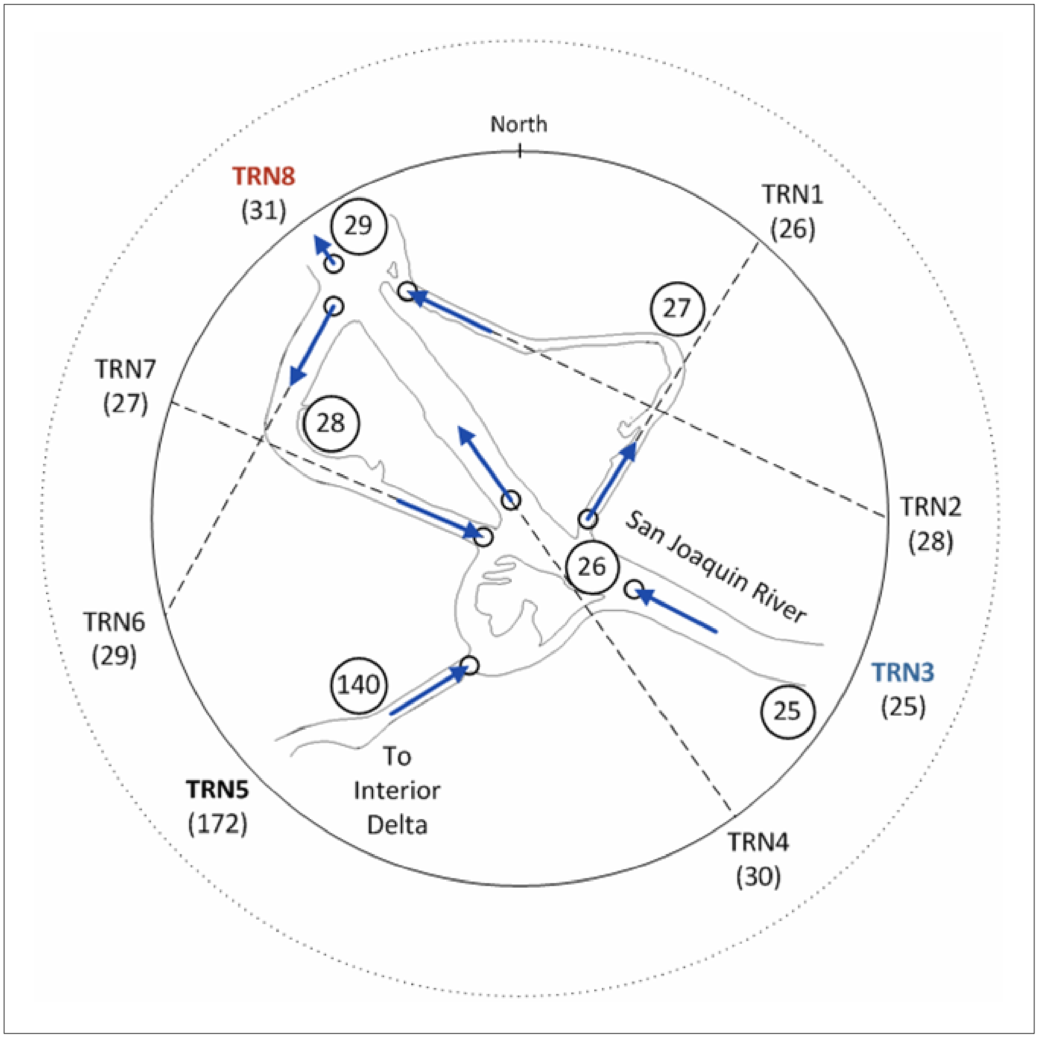


Figure 6. TRN: Plan-view of Turner Cut Junction. *See* Figure 3 for description of elements.

Turner Cut (TRN) Junction:

Flows

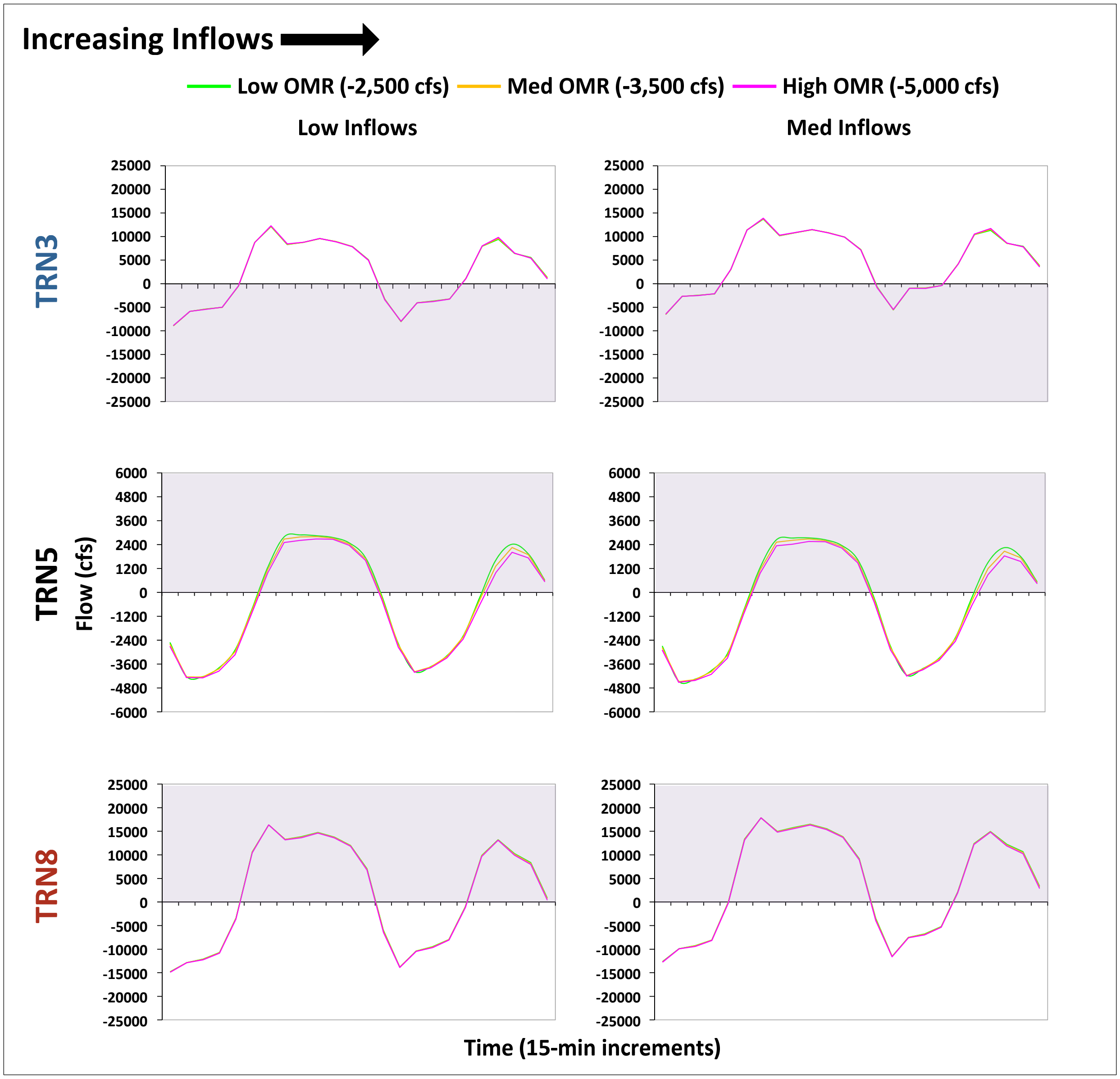


Figure 7. TRN: Flow in Turner Cut Junction Channels over 24 Hours. Time is on the x-axis; magnitude of flow is on the y-axis. Curve color indicates export level. Chanel designations are as indicated in Table 2. For channel TRN5, flow displayed in the shaded area is away from the interior Delta. For the other channels, flow displayed in the shaded area is away from the center of the junction.

Turner Cut (TRN) Junction:

Proportion of Flows to Interior Delta

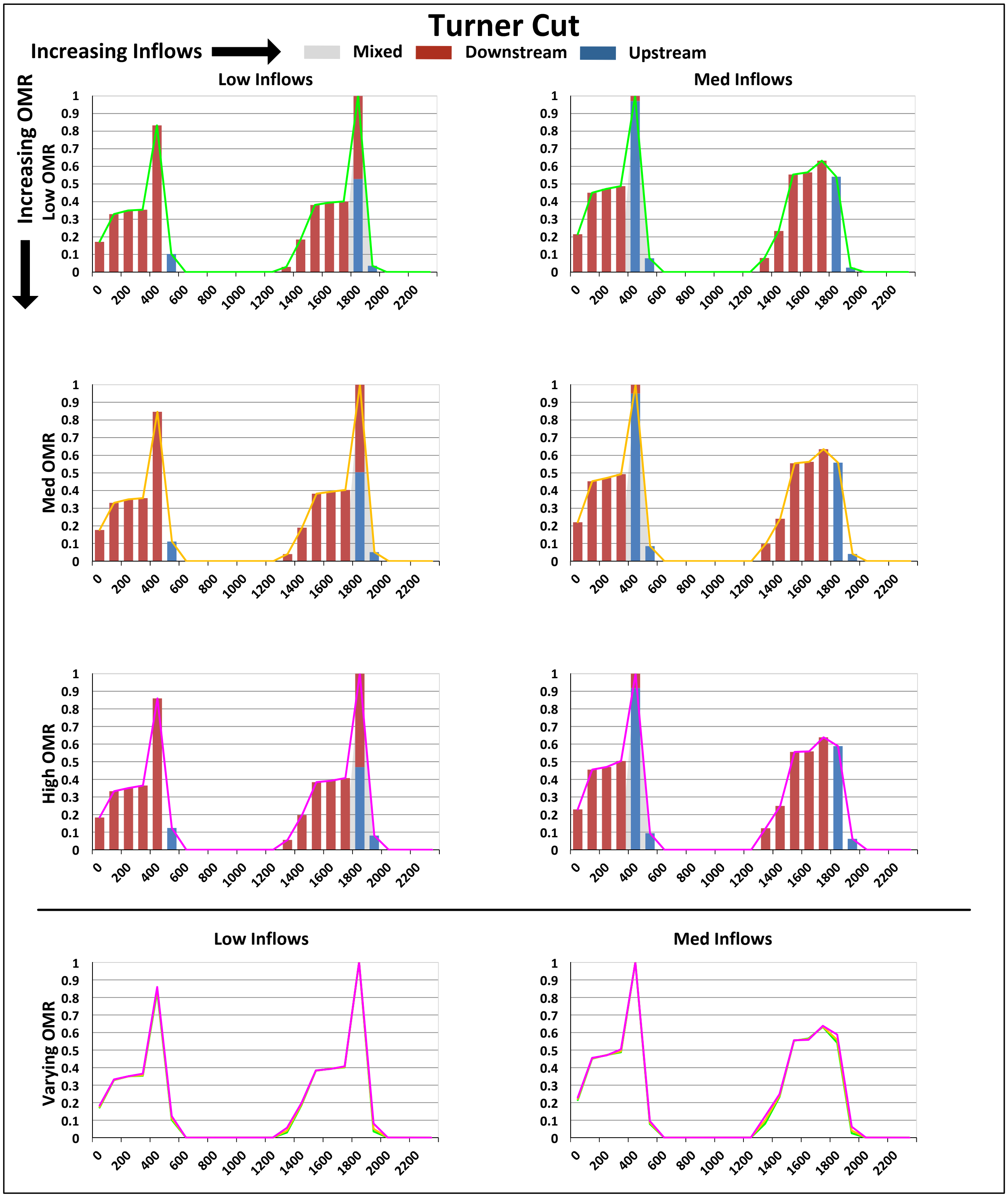


Figure 8. TRN: Proportion of Flow to Interior Delta at Turner Cut. *See* Figure 5 for description of elements.

Columbia Cut (COL) Junction:

Junction Plan View

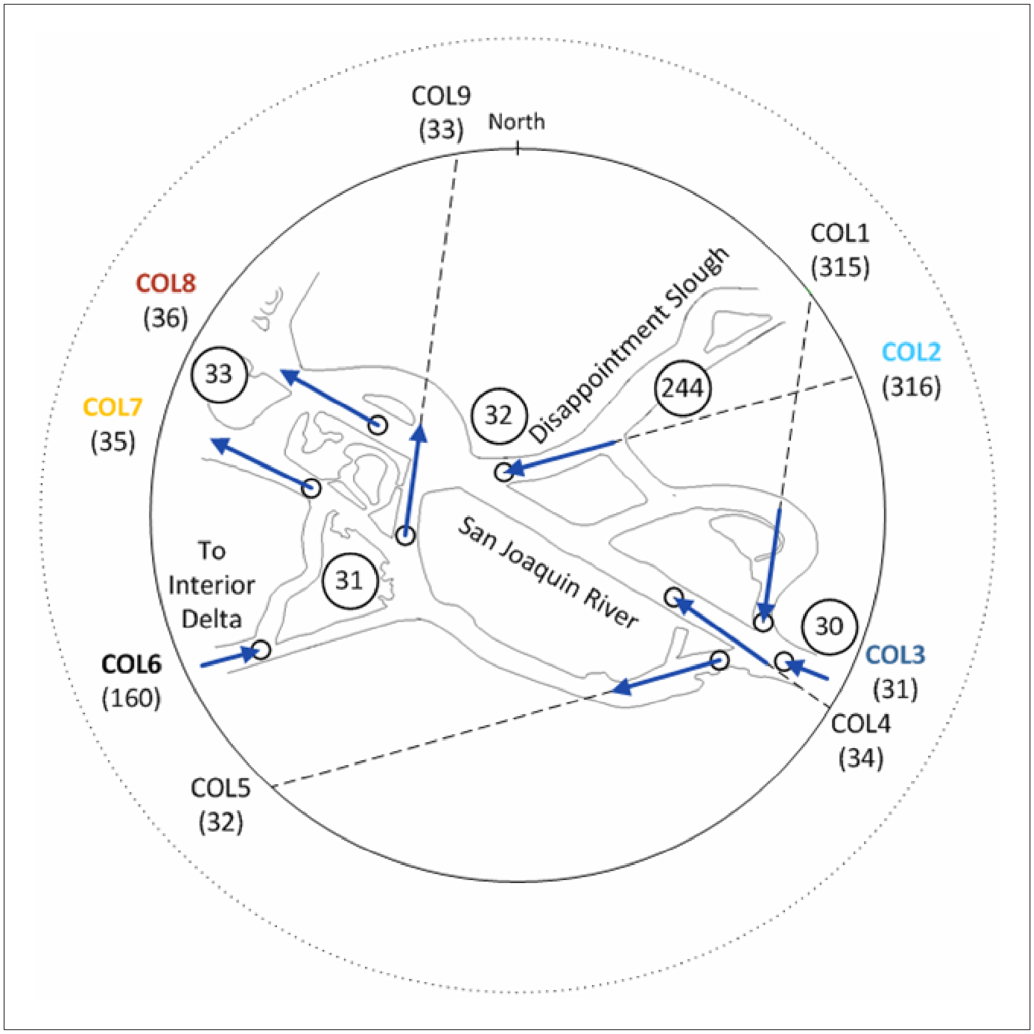


Figure 9. COL: Plan-view of Columbia Cut Junction. *See* Figure 3 for description of elements.

Columbia Cut (COL) Junction:

Flows

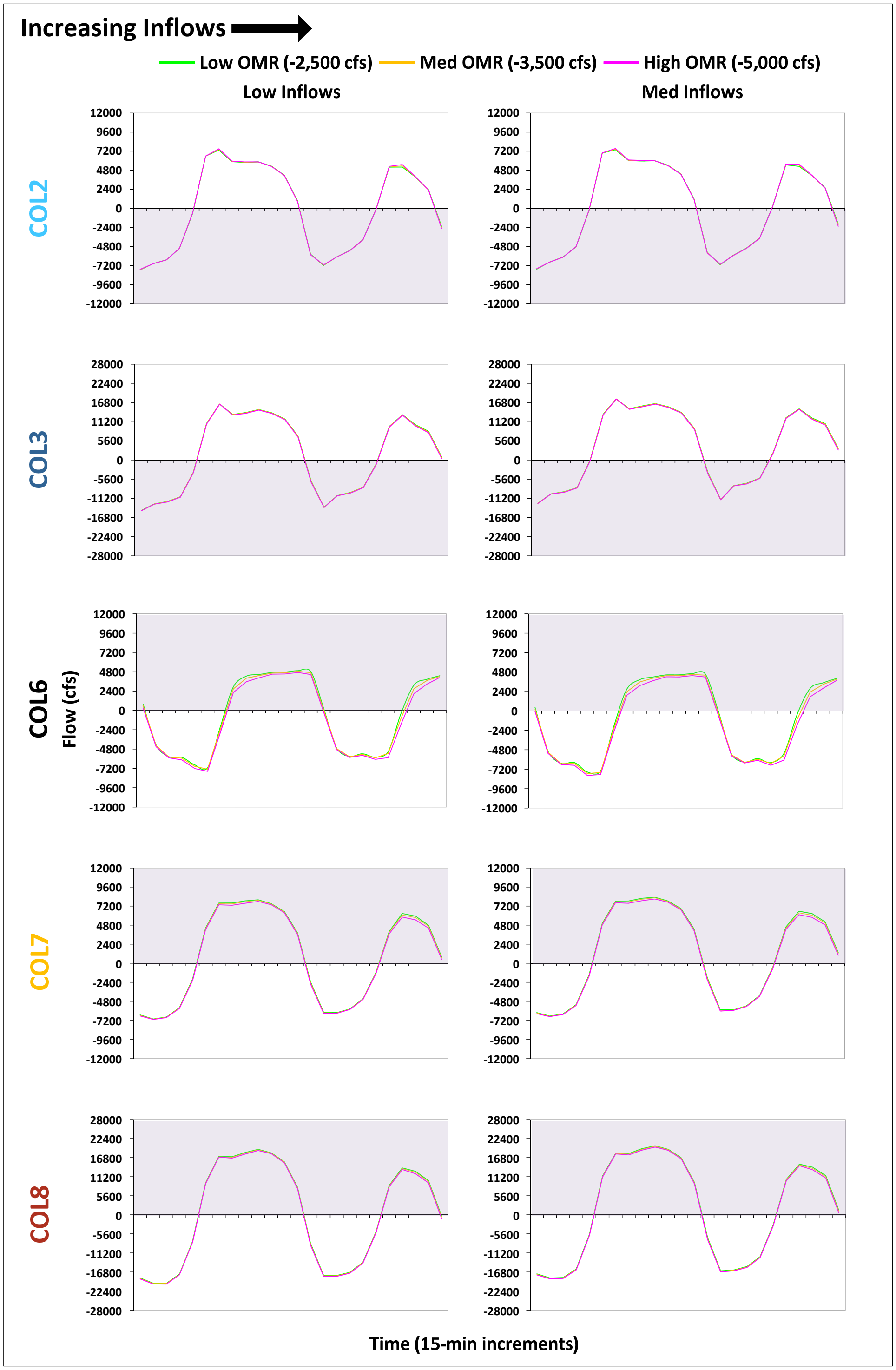


Figure 10. COL: Flow in Columbia Cut Junction Channels over 24 Hours. *See* Figure 7 for description of elements. For channel COL6, flow displayed in the shaded area is away from the interior Delta; for the other channels, flow displayed in the shaded area is away from the center of the junction.

Columbia Cut (COL) Junction:

Proportion of Flow to Interior Delta

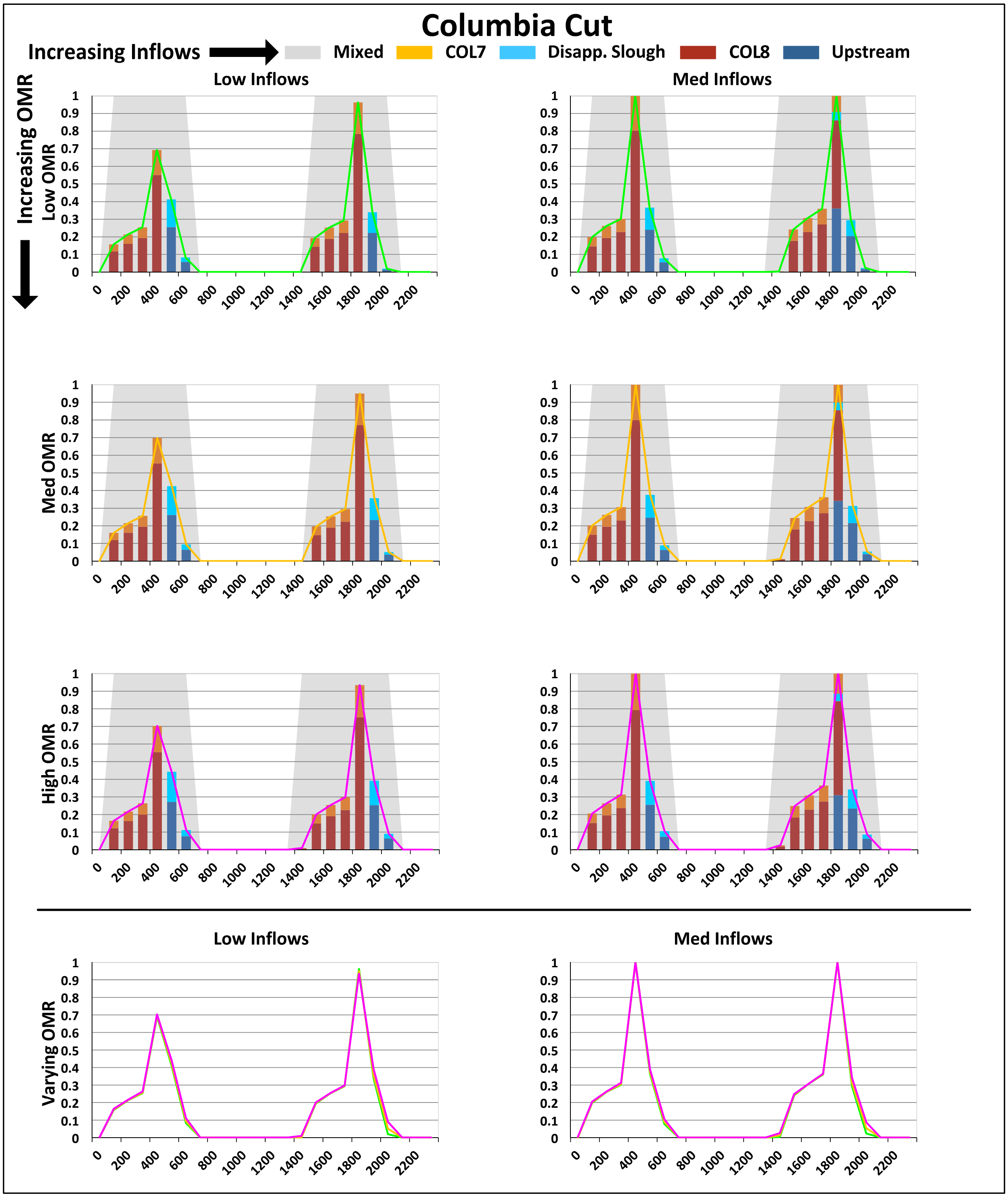


Figure 11. COL: Proportion of Flow to Interior Delta at Columbia Cut. *See* Figure 5 for description of elements.

Middle River (MRV) Junction:

Junction Plan View

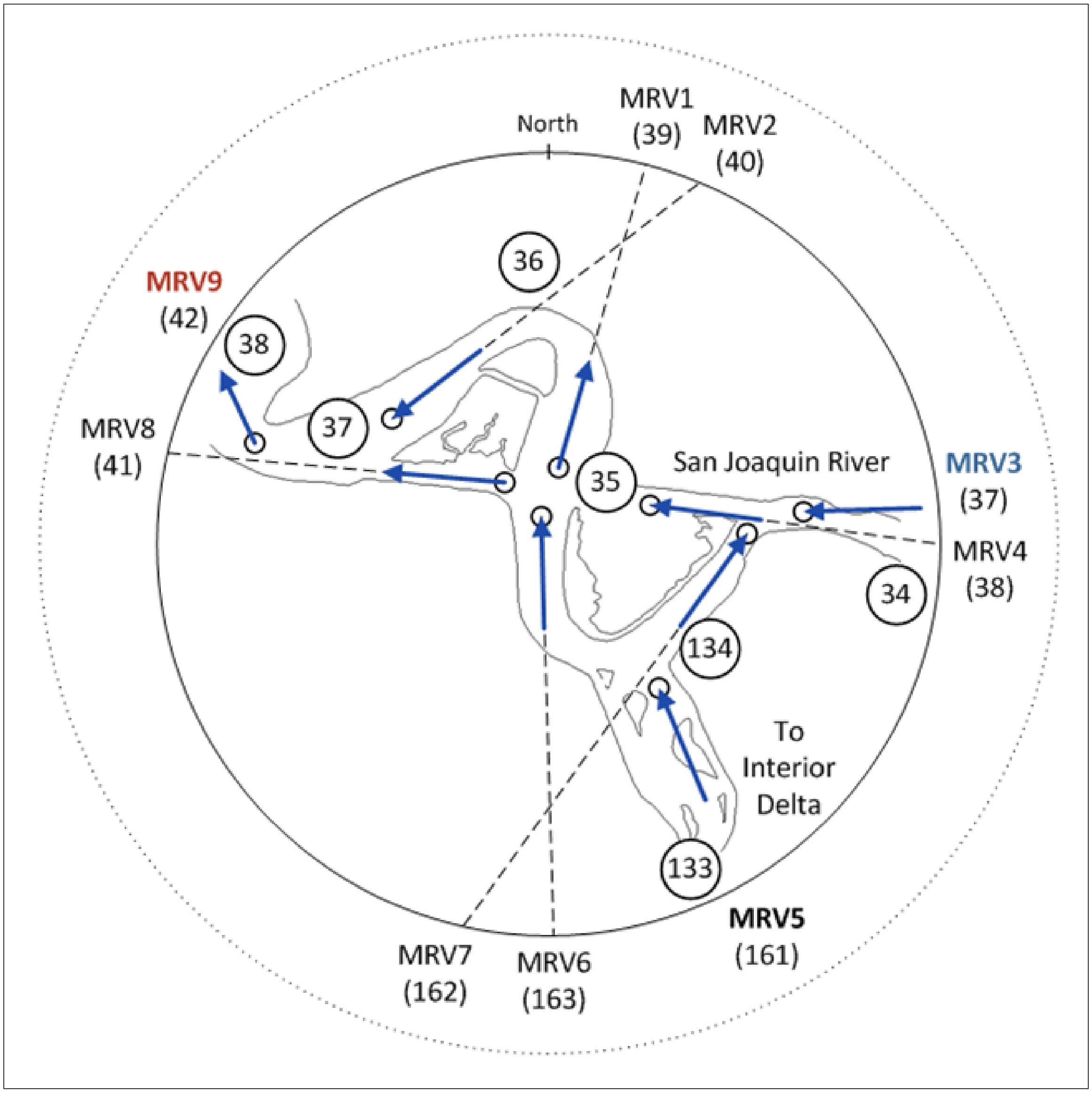


Figure 12. MRV: Plan-view of Middle River Junction. *See* Figure 3 for description of elements.

Middle River (MRV) Junction:

Flows

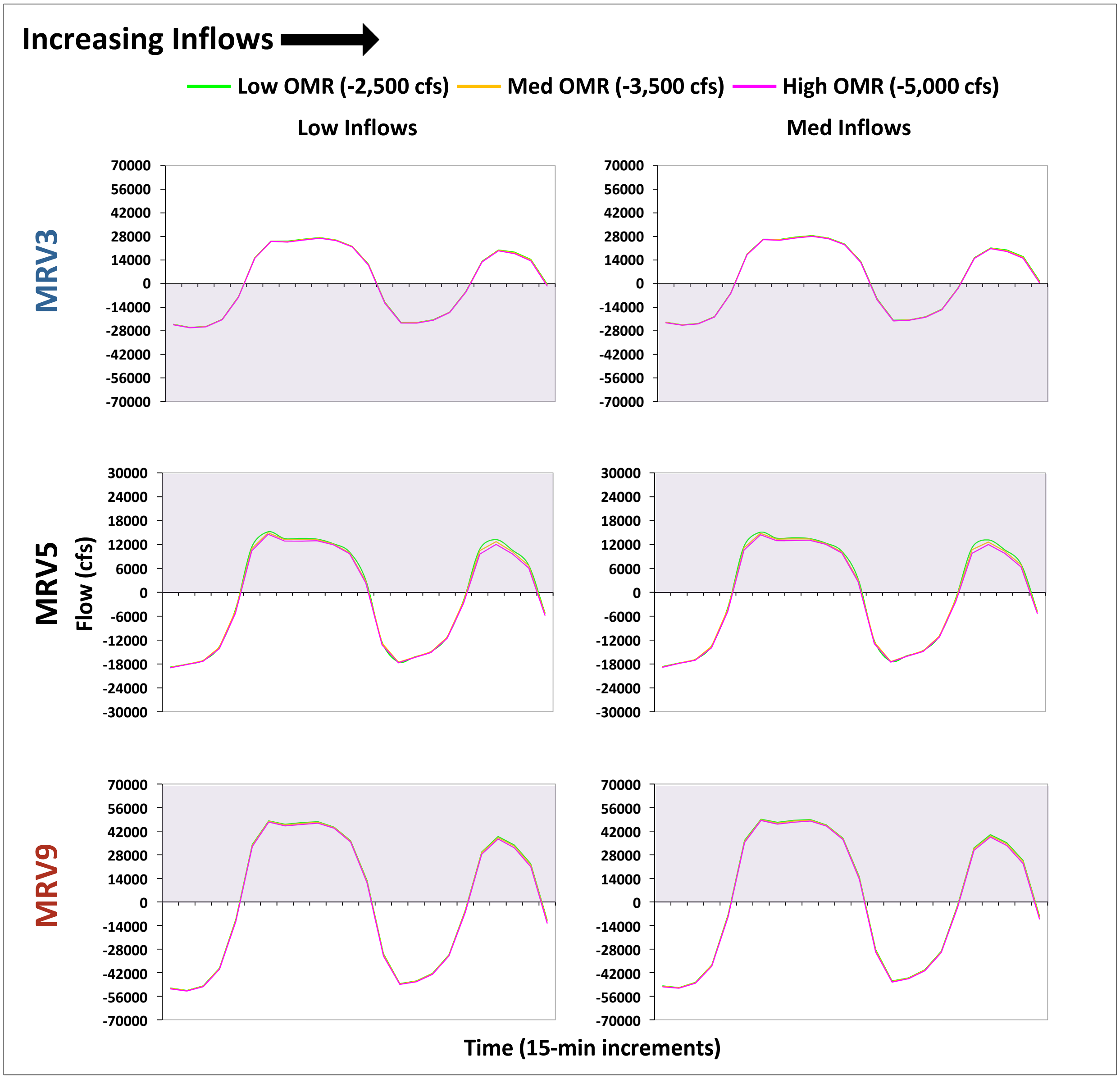


Figure 13. MRV: Flow in Middle River Junction Channels over 24 Hours. *See* Figure 7 for description of elements. For channel MRV5, flow displayed in the shaded area is away from the interior Delta; for the other channels, flow displayed in the shaded area is away from the center of the junction.

Middle River (MRV) Junction:

Proportion of Flow to Interior Delta

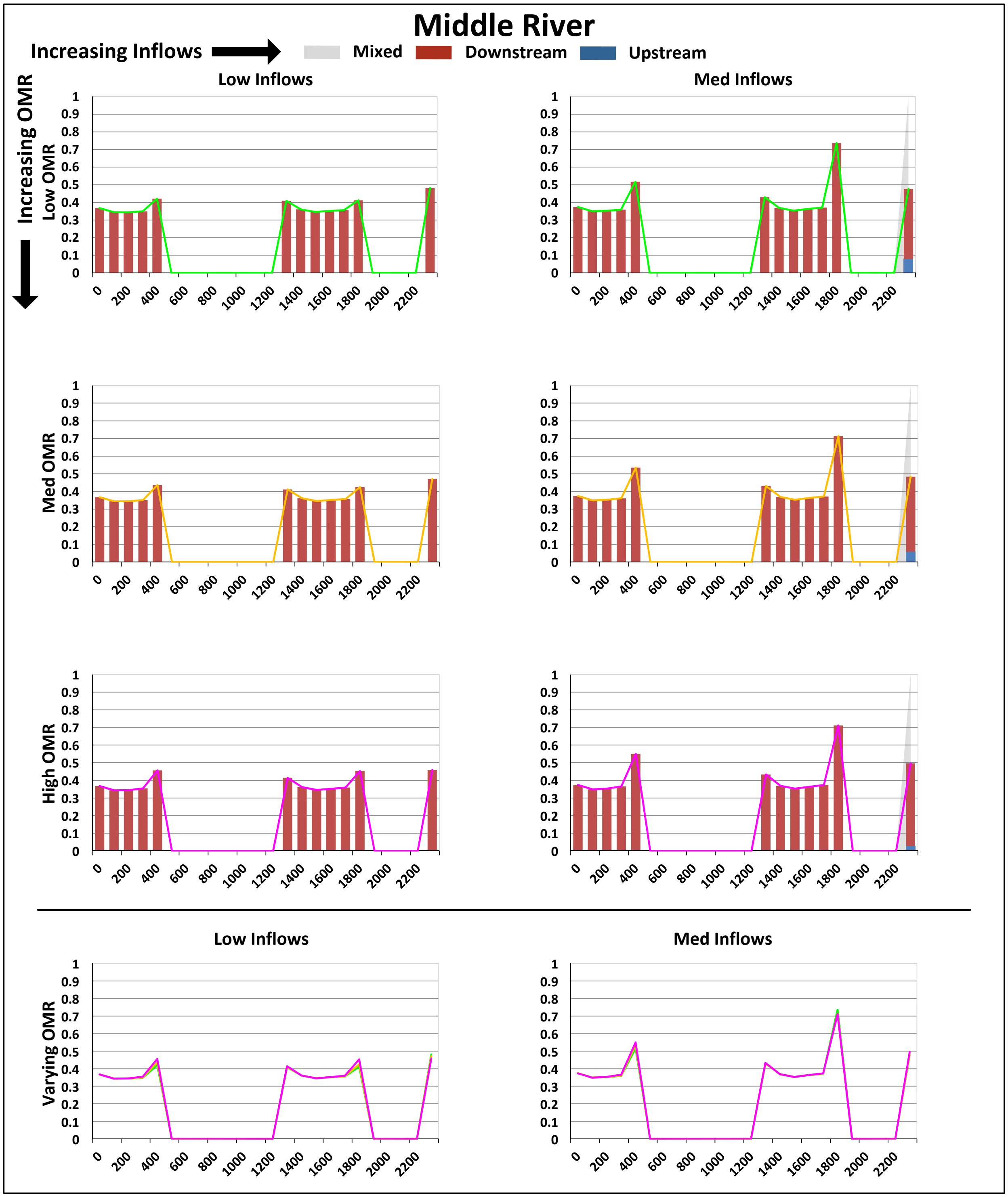


Figure 14. MRV: Proportion of Flow to Interior Delta at Middle River. *See* Figure 5 for description of elements.

Old River (ORV) Junction:

Junction Plan View

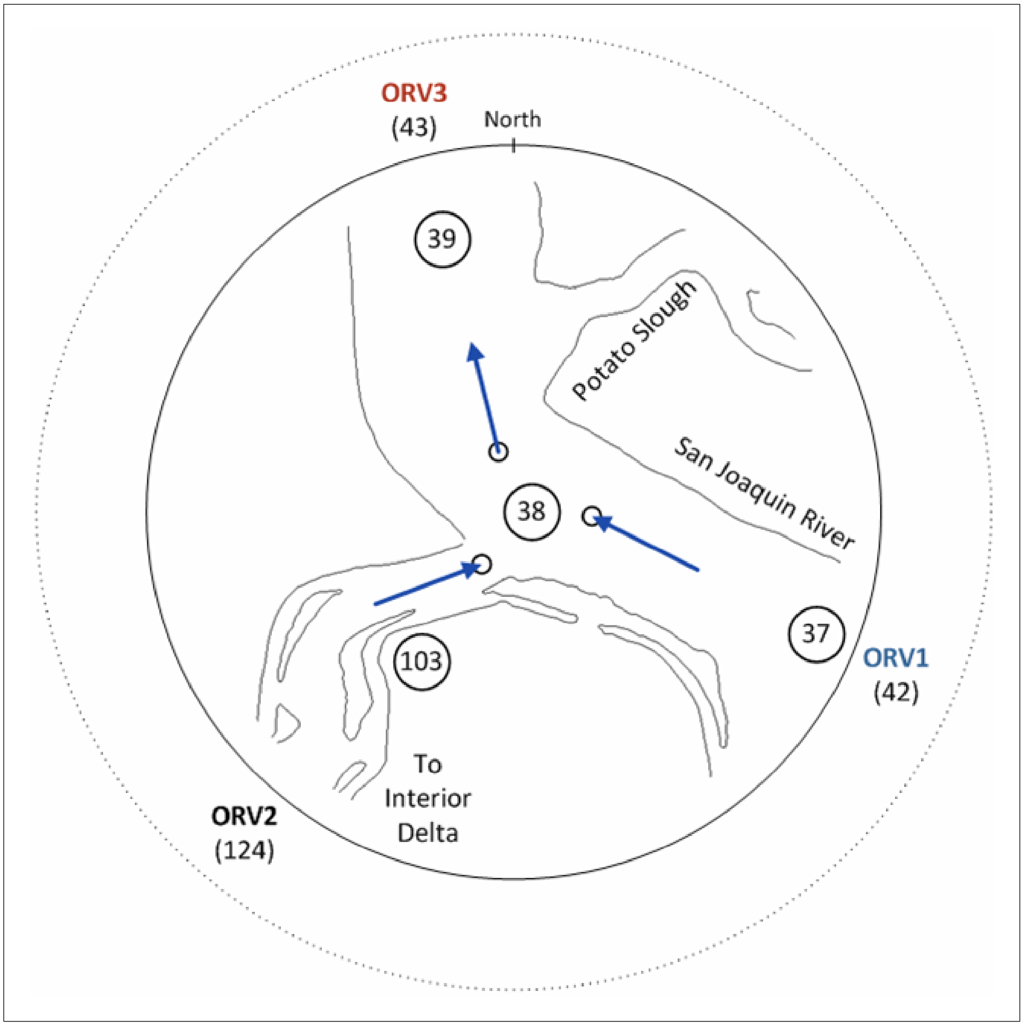


Figure 15. ORV: Plan-view of Old River Junction. *See* Figure 3 for description of elements.

Old River (ORV) Junction:

Flows

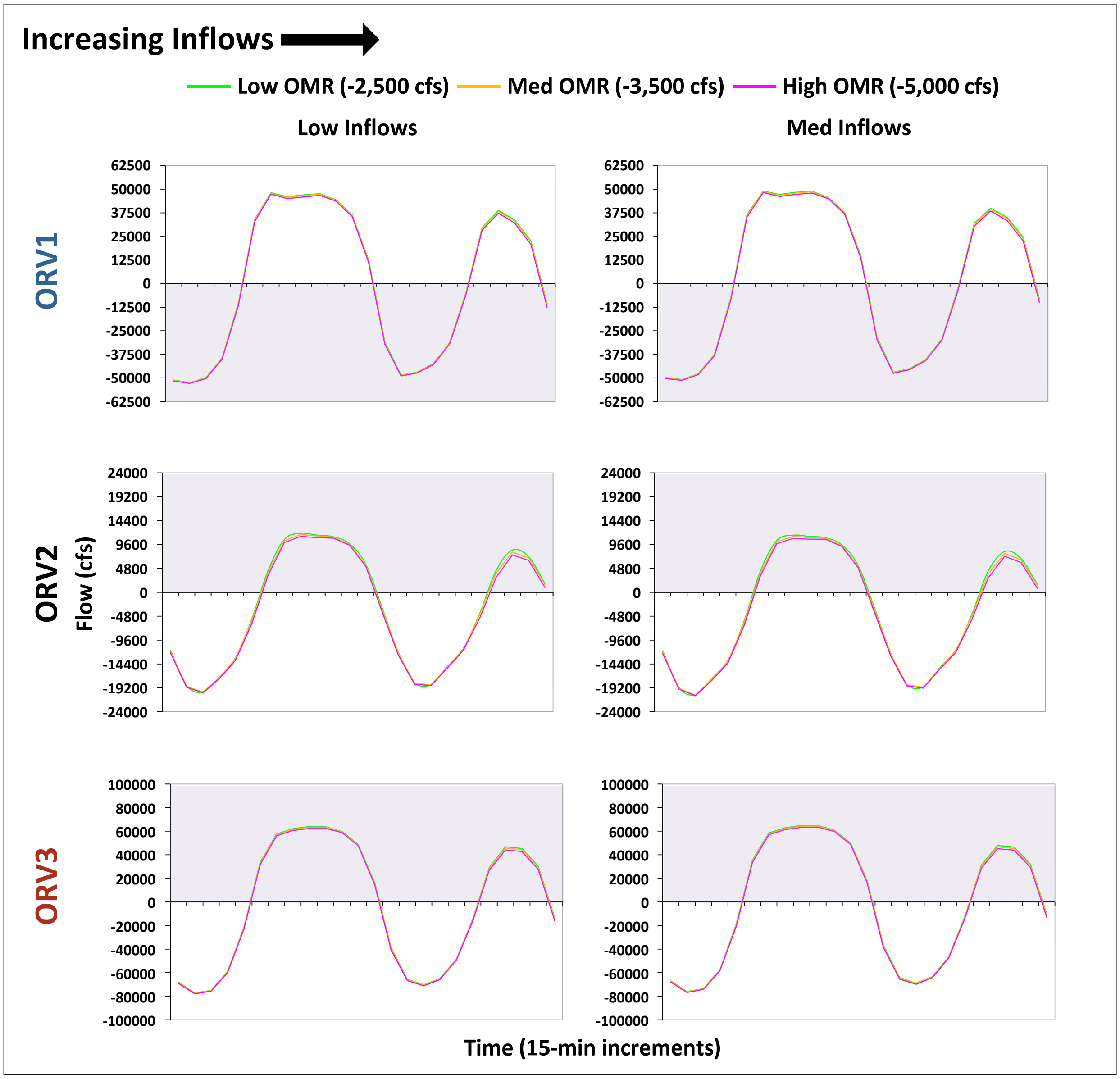


Figure 16. ORV: Flow in Mouth of Old River Junction Channels over 24 Hours. *See* Figure 7 for description of elements. For channel ORV2, flow displayed in the shaded area is away from the interior Delta; for the other channels, flow displayed in the shaded area is away from the center of the junction.

Old River (ORV) Junction:

Proportion of Flow to Interior Delta

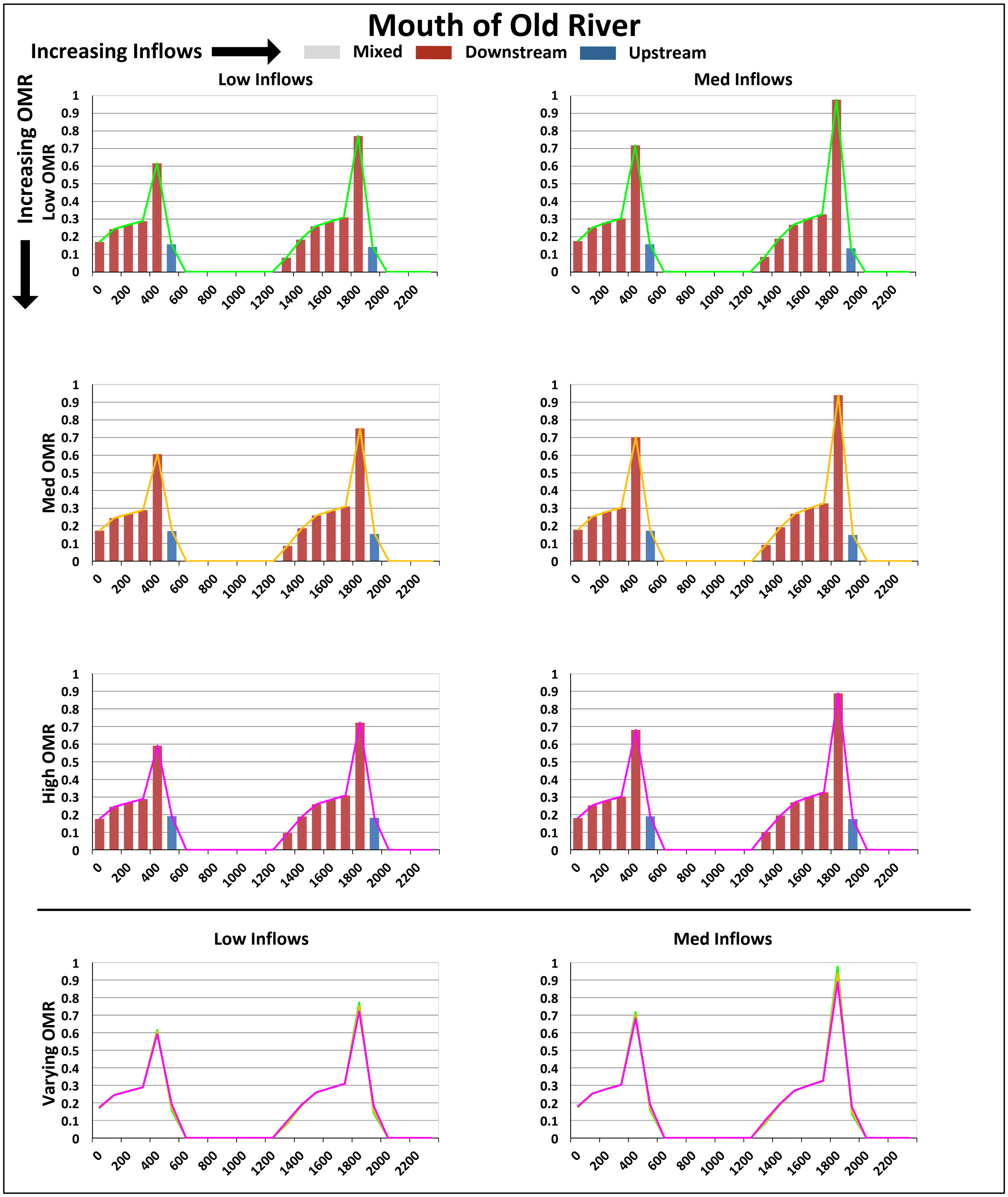


Figure 17. ORV: Proportion of Flow to Interior Delta at Mouth of Old River. *See* Figure 5 for description of elements.

Daily Proportion of Flows to Interior Delta:

All Junctions

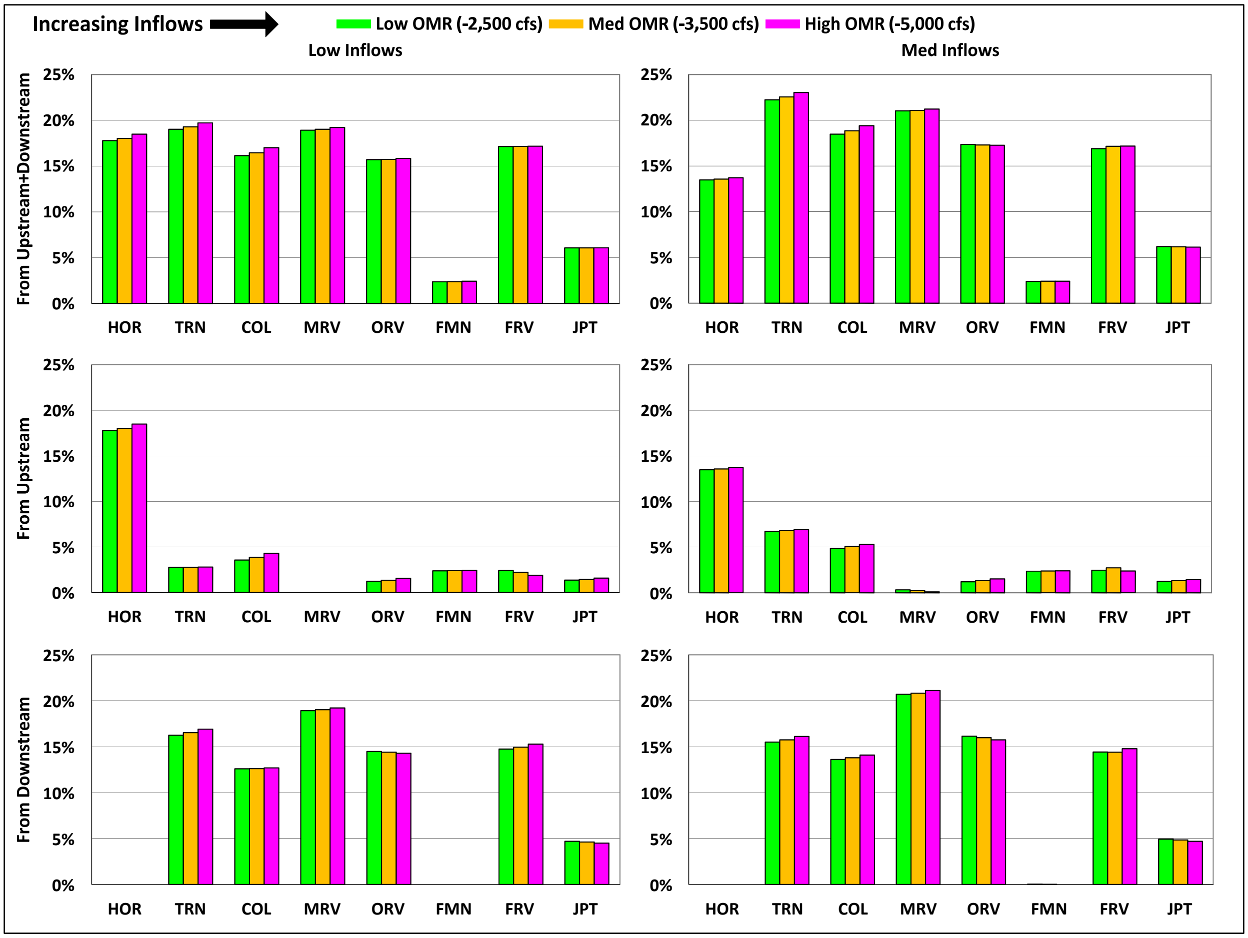


Figure 18. Total Proportion of Flow to Interior Delta over 24 Hours. Data are displayed by junction and export level. Junctions are on the x-axis; proportion of flow is on the y-axis. Bar color indicates export level. Graphs are arranged by increasing inflows, and by water source (i.e., upstream or downstream from the junction).

Table 3. Total Proportion of Flow to Interior Delta over 24 Hours. Data are displayed by junction and OMR level. Graphs are arranged by inflow level and water source (i.e., upstream or downstream from the junction).

From Upstream+Downstream: Low Inflows

Junction	OMR		
	-2500	-3500	-5000
HOR	17.78%	18.03%	18.48%
TRN	19.03%	19.30%	19.72%
COL	16.14%	16.46%	17.01%
MRV	18.92%	19.02%	19.21%
ORV	15.71%	15.75%	15.84%
FMN	2.38%	2.39%	2.42%
FRV	17.15%	17.16%	17.18%
JPT	6.07%	6.07%	6.09%

From Upstream: Low Inflows

Junction	OMR		
	-2500	-3500	-5000
HOR	17.78%	18.03%	18.48%
TRN	2.78%	2.77%	2.81%
COL	3.56%	3.86%	4.32%
MRV	0.00%	0.00%	0.00%
ORV	1.25%	1.35%	1.56%
FMN	2.38%	2.39%	2.42%
FRV	2.41%	2.22%	1.90%
JPT	1.37%	1.45%	1.59%

From Downstream: Low Inflows

Junction	OMR		
	-2500	-3500	-5000
HOR	0.00%	0.00%	0.00%
TRN	16.25%	16.52%	16.91%
COL	12.58%	12.60%	12.68%
MRV	18.92%	19.02%	19.21%
ORV	14.47%	14.39%	14.28%
FMN	0.00%	0.00%	0.00%
FRV	14.74%	14.95%	15.28%
JPT	4.70%	4.62%	4.50%

From Upstream+Downstream: Med Inflows

Junction	OMR		
	-2500	-3500	-5000
HOR	13.48%	13.57%	13.73%
TRN	22.24%	22.55%	23.04%
COL	18.47%	18.86%	19.40%
MRV	21.04%	21.07%	21.22%
ORV	17.35%	17.30%	17.27%
FMN	2.40%	2.40%	2.41%
FRV	16.90%	17.15%	17.18%
JPT	6.20%	6.17%	6.14%

From Upstream: Med Inflows

Junction	OMR		
	-2500	-3500	-5000
HOR	13.48%	13.57%	13.73%
TRN	6.73%	6.81%	6.93%
COL	4.87%	5.07%	5.32%
MRV	0.33%	0.24%	0.11%
ORV	1.22%	1.33%	1.52%
FMN	2.38%	2.39%	2.41%
FRV	2.48%	2.74%	2.40%
JPT	1.26%	1.33%	1.45%

From Downstream: Med Inflows

Junction	OMR		
	-2500	-3500	-5000
HOR	0.00%	0.00%	0.00%
TRN	15.50%	15.74%	16.10%
COL	13.60%	13.79%	14.09%
MRV	20.70%	20.82%	21.11%
ORV	16.14%	15.97%	15.75%
FMN	0.02%	0.01%	0.00%
FRV	14.42%	14.41%	14.78%
JPT	4.94%	4.84%	4.69%

Table 4. Change in Total Proportion of Flow to Interior Delta over 24 Hours with Increasing Inflows. Values are for change in total proportion relative to low inflows. Data are displayed by junction and OMR level. Graphs are arranged by inflow level and water source (i.e., upstream or downstream from the junction).

From Upstream+Downstream: Med Inflows

Junction	OMR		
	-2500	-3500	-5000
HOR	-4.30%	-4.46%	-4.76%
TRN	3.21%	3.25%	3.32%
COL	2.33%	2.40%	2.40%
MRV	2.12%	2.05%	2.01%
ORV	1.64%	1.56%	1.43%
FMN	0.02%	0.01%	-0.01%
FRV	-0.25%	-0.01%	0.00%
JPT	0.13%	0.10%	0.06%

From Upstream: Med Inflows

Junction	OMR		
	-2500	-3500	-5000
HOR	-4.30%	-4.46%	-4.76%
TRN	3.96%	4.03%	4.12%
COL	1.31%	1.21%	0.99%
MRV	0.33%	0.24%	0.11%
ORV	-0.03%	-0.02%	-0.03%
FMN	0.00%	0.00%	-0.01%
FRV	0.07%	0.53%	0.50%
JPT	-0.11%	-0.11%	-0.14%

From Downstream: Med Inflows

Junction	OMR		
	-2500	-3500	-5000
HOR	0.00%	0.00%	0.00%
TRN	-0.75%	-0.78%	-0.81%
COL	1.02%	1.19%	1.40%
MRV	1.79%	1.80%	1.89%
ORV	1.67%	1.58%	1.46%
FMN	0.02%	0.01%	0.00%
FRV	-0.32%	-0.54%	-0.50%
JPT	0.24%	0.21%	0.19%

Table 5. Change in Total Proportion of Flow to Interior Delta over 24 Hours with decreasing OMR. Values are for change in percentage of total proportion relative to -2500 cfs OMR. Data are displayed by junction and OMR level. Graphs are arranged by inflow level and water source (i.e., upstream or downstream from the junction).

From Upstream+Downstream: Low Inflows

Junction	OMR	
	-3500	-5000
HOR	0.24%	0.70%
TRN	0.27%	0.69%
COL	0.32%	0.87%
MRV	0.11%	0.30%
ORV	0.03%	0.13%
FMN	0.01%	0.05%
FRV	0.01%	0.03%
JPT	0.00%	0.02%

From Upstream: Low Inflows

Junction	OMR	
	-3500	-5000
HOR	0.24%	0.70%
TRN	0.00%	0.03%
COL	0.30%	0.76%
MRV	0.00%	0.00%
ORV	0.11%	0.31%
FMN	0.01%	0.05%
FRV	-0.19%	-0.51%
JPT	0.08%	0.21%

From Downstream: Low Inflows

Junction	OMR	
	-3500	-5000
HOR	0.00%	0.00%
TRN	0.27%	0.66%
COL	0.02%	0.10%
MRV	0.11%	0.30%
ORV	-0.07%	-0.18%
FMN	0.00%	0.00%
FRV	0.21%	0.54%
JPT	-0.08%	-0.20%

From Upstream+Downstream: Med Inflows

Junction	OMR	
	-3500	-5000
HOR	0.09%	0.24%
TRN	0.31%	0.80%
COL	0.39%	0.93%
MRV	0.03%	0.18%
ORV	-0.05%	-0.08%
FMN	0.00%	0.01%
FRV	0.25%	0.28%
JPT	-0.03%	-0.05%

From Upstream: Med Inflows

Junction	OMR	
	-3500	-5000
HOR	0.09%	0.24%
TRN	0.07%	0.20%
COL	0.20%	0.44%
MRV	-0.09%	-0.22%
ORV	0.11%	0.31%
FMN	0.01%	0.04%
FRV	0.26%	-0.09%
JPT	0.07%	0.19%

From Downstream: Med Inflows

Junction	OMR	
	-3500	-5000
HOR	0.00%	0.00%
TRN	0.24%	0.60%
COL	0.19%	0.49%
MRV	0.12%	0.40%
ORV	-0.17%	-0.39%
FMN	-0.01%	-0.02%
FRV	-0.01%	0.36%
JPT	-0.10%	-0.24%

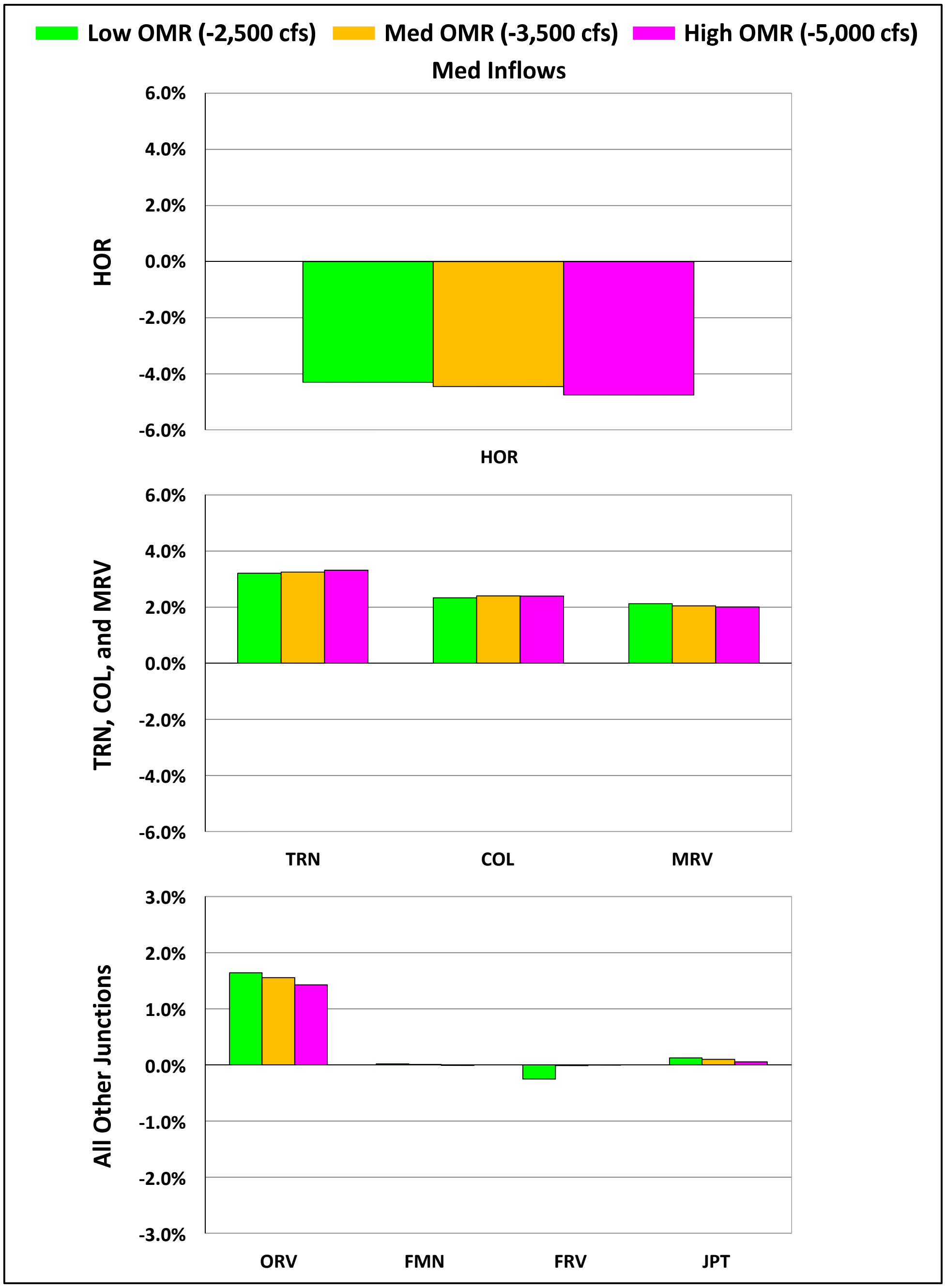


Figure 19. Change in Total Proportion of Flow to Interior Delta over 24 Hours as SJR inflows increase from 3,000 cfs to 6,000 cfs. Values are for change in total proportion for inflows at 6,000 cfs relative to 3,000 cfs. Data are displayed by junction and for OMR flow level.

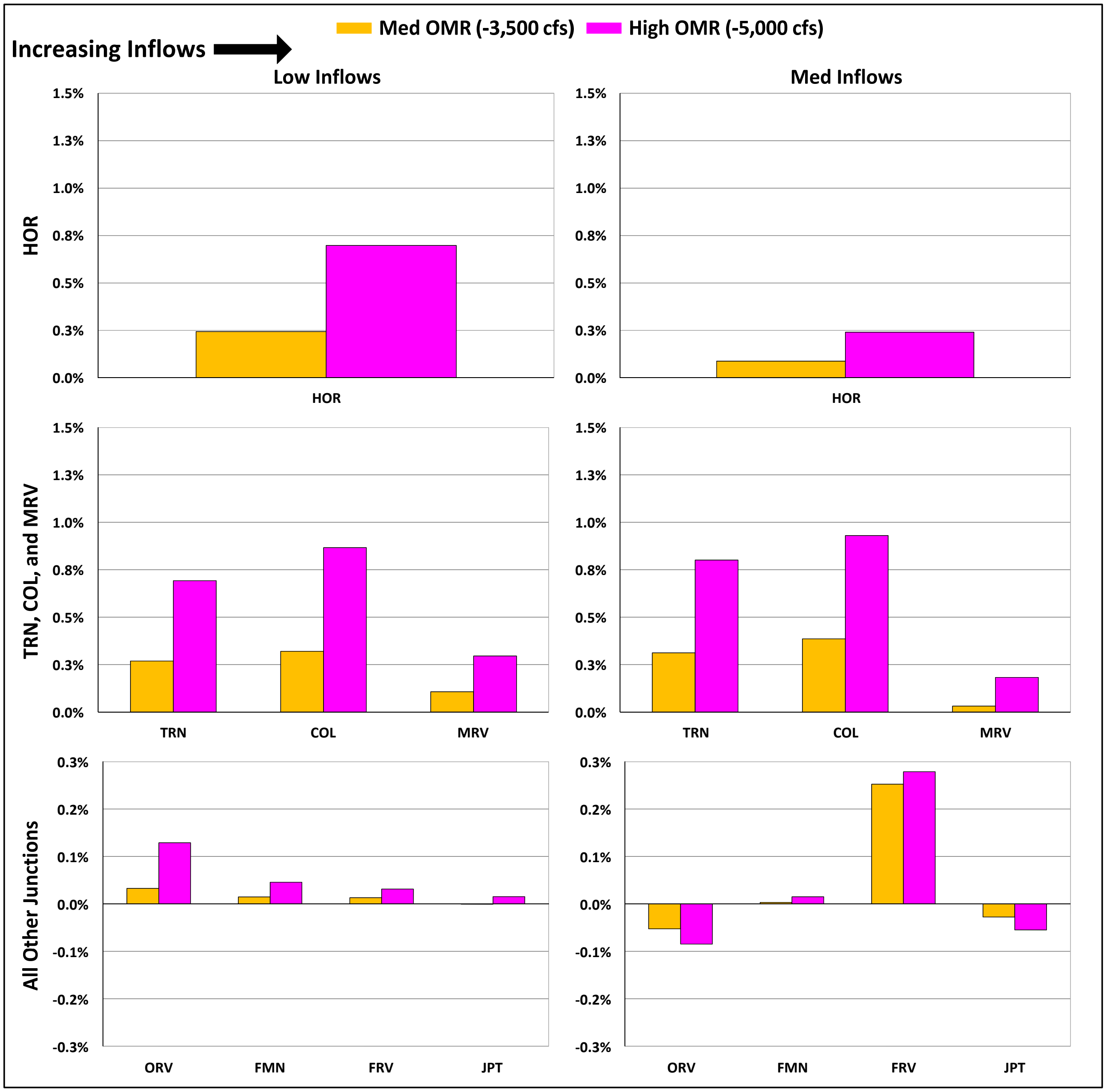
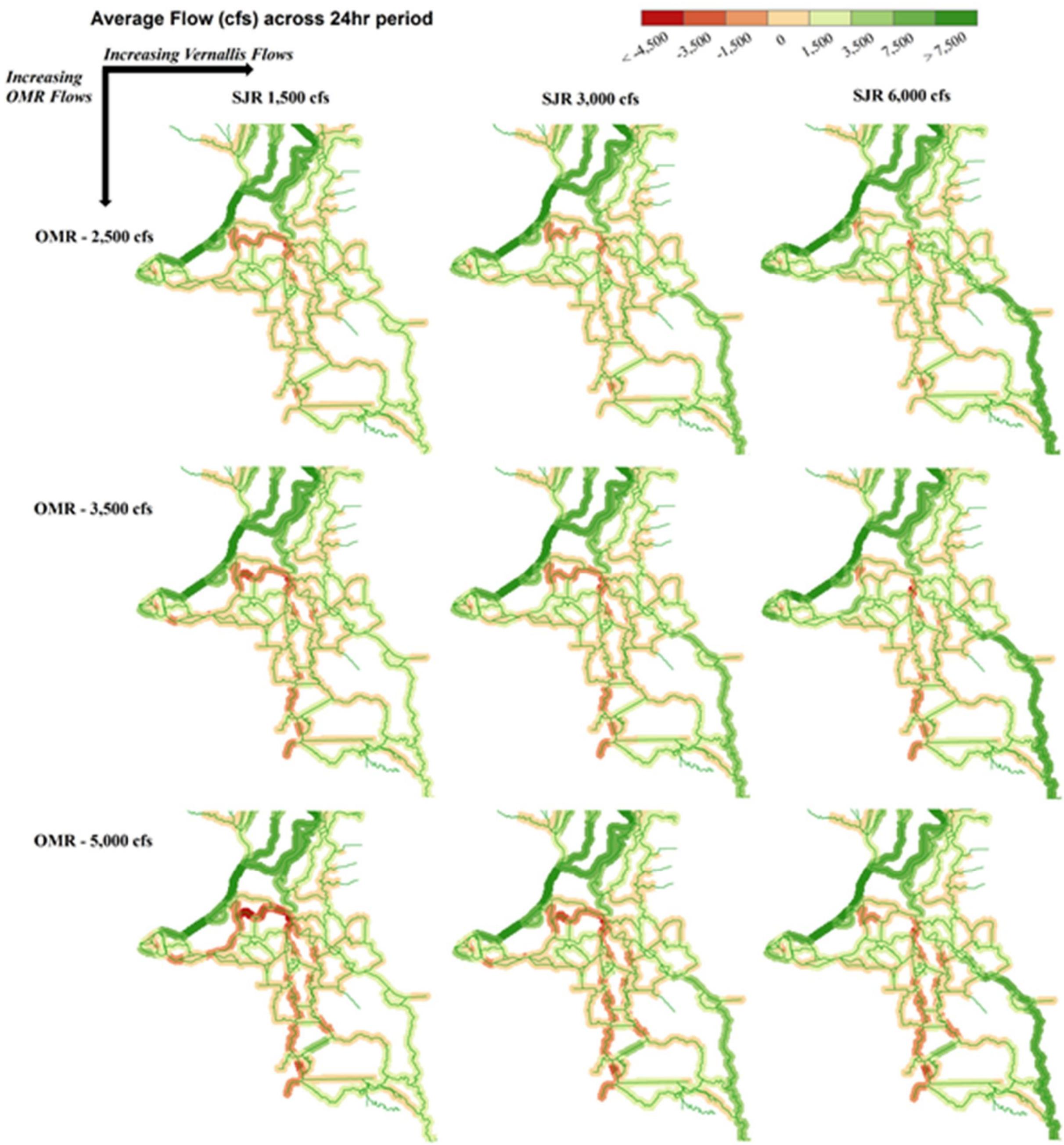


Figure 20. Change in Total Proportion of Flow to Interior Delta over 24 Hours with OMR flows decreasing from -2500 cfs to -3500 cfs, and from -2500 cfs to -5000 cfs. Values are for change in percentage of total proportion relative to OMR at -2500 cfs. Data are displayed by junction and OMR flow level. Graphs are arranged by inflow level.

Spatial and Longitudinal (upstream-downstream) Patterns in Delta Hydrodynamics

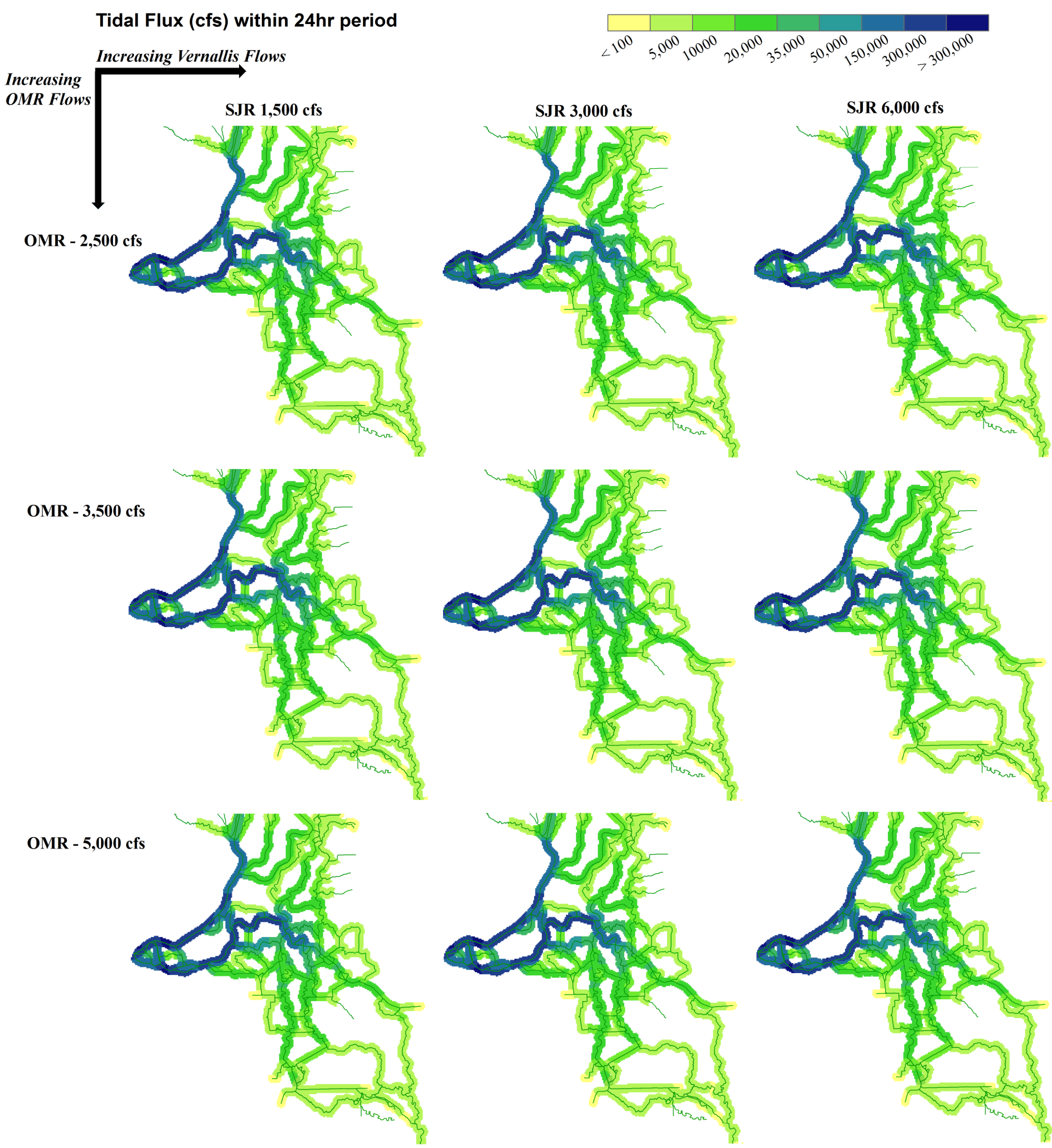
(Note: these findings will be reported in a separate manuscript from the junction scale analysis shown on previous pages)

Average Daily Flow



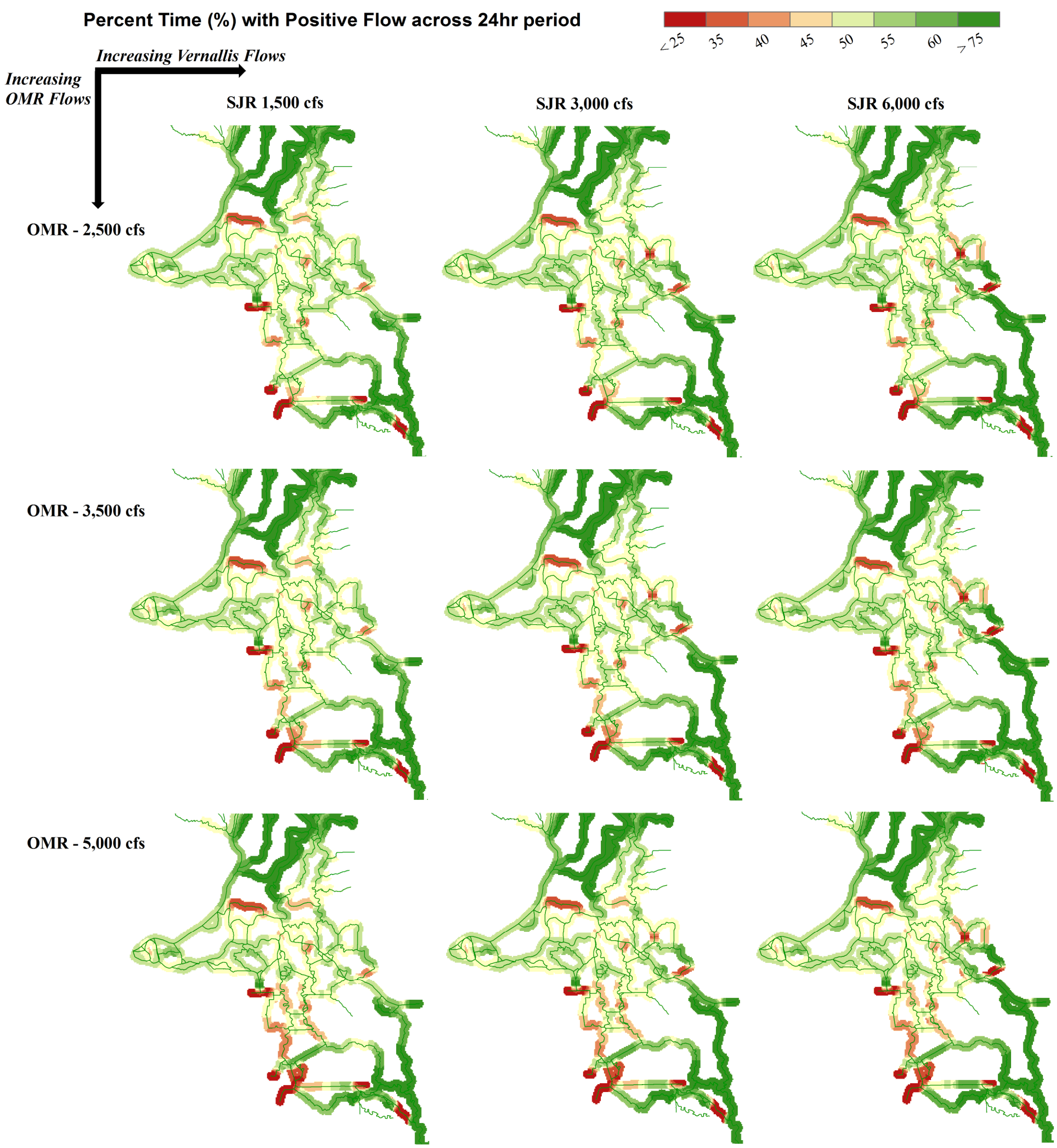
Tidal Flux

(difference between max and min observed flows)



Percent Time with Positive Flows

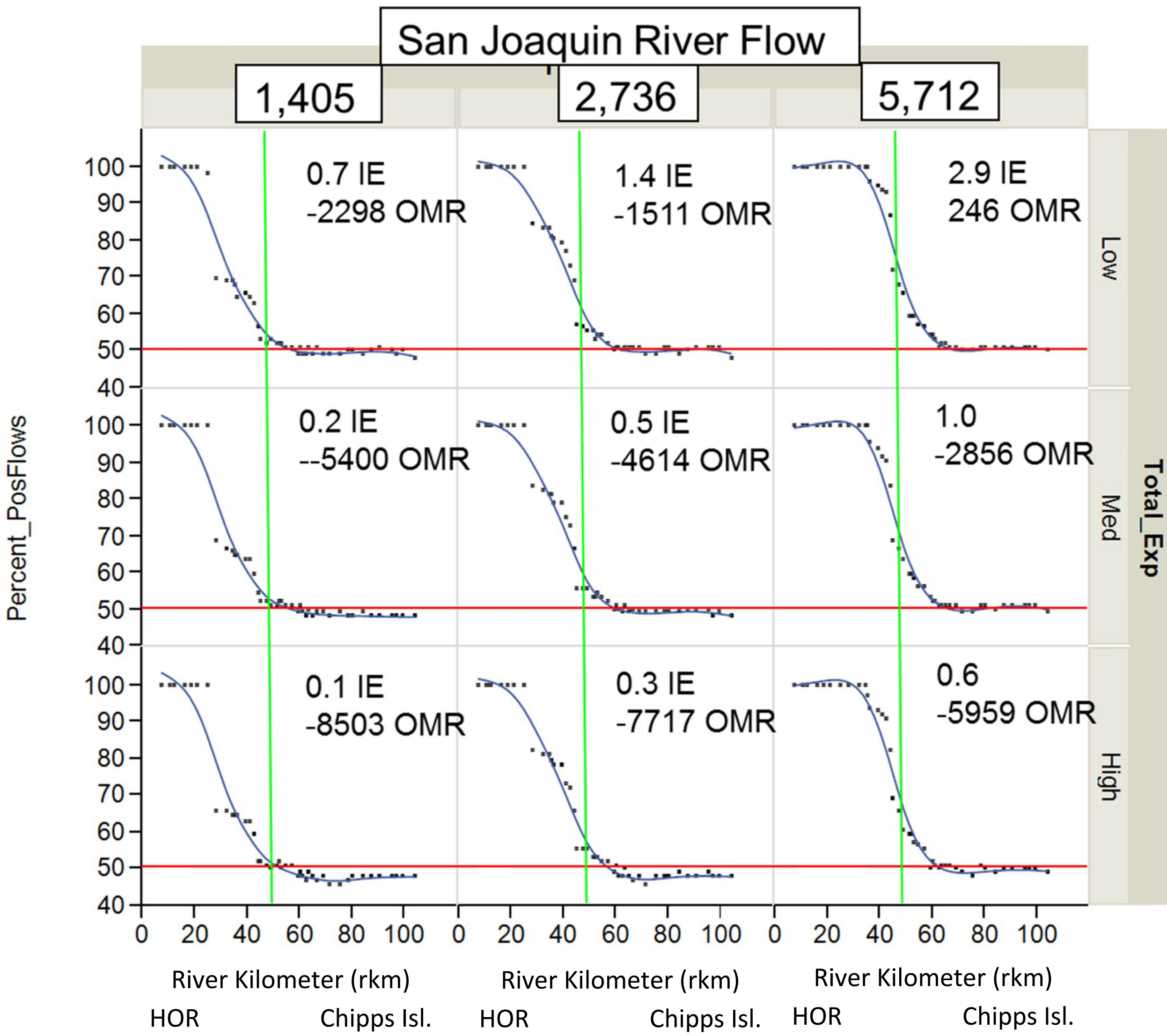
(<50% = diversions, ~50% = tidal, >50% = river inflow)



Mainstem San Joaquin River (HOR to Chipps Isl.):

Percentage of Time with Positive Flows

(<50% = diversions, ~50% = tidal, >50% = river inflow)



Mouth of Old River to Export Facilities:

Percentage of Time with Positive Flows

(<50% = diversions, ~50% = tidal, >50% = river inflow)